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June 1966

Westinghouse Astronuclear Laboratory

HHT-7 FILLER STRIP CORROSION TEST MODEL:
TEST REPORT NO. 3, HOT BUFFER TYPE PERIPHERAL CORE DESIGN
(Title Unclassified)

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Prepared by:

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ABSTRACT

Post test examination of the graphite material from reactors tested to date has revealed that the rate of hydrogen corrosion of the graphite at high temperatures is still one of the primary factors limiting the life of current NERVA reactor designs.

In order to increase the life of current reactors, it is necessary to minimize the effects of hydrogen-graphite corrosion in critical problem areas, e. g. , fuel element bore corrosion, support block corrosion, and core peripheral corrosion.

In an effort to study one phase of the corrosion problem in the core periphery, a filler strip corrosion test program utilizing a small diameter core model was initiated in October, 1964. This program is directed to provide experimental information to qualitatively evaluate by comparison core peripheral corrosion; its behavior, and its effects on peripheral type components. Since the beginning of the program, three filler strip corrosion test models were tested. Through redesigns that incorporated advanced development techniques, each model test has demonstrated an increased improvement in its ability to reproduce representative reactor type corrosion behavior. The results from these tests are useful in evaluating current and proposed core peripheral design configurations.

A total of five filler strip corrosion model tests have been conducted since this program was initiated. This report is the third to be documented and summarizes the results of a test conducted with a proposed peripheral core design, i. e. , The Hot Buffer Periphery.

In this report, the test apparatus and environmental conditions are described and the results obtained are discussed. Contained in this report is general information on the corrosion behavior obtained in a small diameter component core model utilizing a hot buffer type peripheral core design.

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1.0 INTRODUCTION

The purpose of this report is to summarize the results of a model test conducted with a hot buffer type periphery. The primary objective of a hot buffer design is to minimize peripheral corrosion by providing some hydrocarbons as a deterrent to fuel element corrosion through radial inflow of a gas inhibitor. In this design, the insulating tile is on the outside diameter of the filler strips which allow the filler strips to operate at about the same temperature as the fuel elements. This design utilizes the filler strips as sacrificial material to generate hydrocarbons by hydrogen-graphite corrosion on its exposed surfaces; thereby, inhibiting fuel element corrosion by forced radial inflow of hydrocarbon gas through the filler strip gaps.

A 3.5 inch diameter core model designated as HHT-7 Build 4 Test 1, was designed to investigate the behavior of the proposed hot buffer type periphery. The Build 4 Test 1 model consists of a hot buffer type peripheral core assembly which includes an uncoated inner core, a half sector of uncoated hot buffer filler strips, and a half sector of ZrC coated filler strips. Each sector included six filler strips.

The objectives of this test were directed to provide experimental information to:

1. qualitatively compare the peripheral corrosion behavior of a hot buffer type peripheral core design with the NRX-A2 and NRX-A3 corrosion behavior previously obtained in the Build 1 test series,¹
2. qualitatively evaluate any difference in corrosion behavior between the sectors of coated and uncoated filler strips, and
3. functionally check-out the operational characteristics of a spring loaded core model.

All test objectives were satisfactorily met.

1. WANL-TME-1135 and WANL-TME-1330.

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The tests were conducted utilizing ambient temperature gas supplied from tube trailers. Two hot hydrogen flow tests were conducted in addition to several preliminary functional check-out tests. The first of the two hot hydrogen flow tests operated for approximately 14 minutes at local core temperature levels in excess of 3000°R . The second test operated a total of 9 minutes with the maximum local core temperature measured, never exceeding 2846°R . Both tests were prematurely terminated as a result of heater element failures.

The corrosion results obtained from the model test show that

1. From the results of the hot buffer tests, the corrosion pattern, once it was started, was generally axial and continuous along the core surface. In contrast the results from the cool periphery tests (Build 1 test series) show local bands of corrosion which existed circumferentially around the core where each of the filler tile plenums were formed. The core surface corrosion obtained in the hot buffer test being relatively light and wide-spread compared to the relatively deep circumferential line corrosion patterns obtained in the cool periphery test.
2. The sector of uncoated hot buffer filler strips utilized as sacrificial material, did not show promise as a method to inhibit core surface corrosion by hydrocarbon generation. The sector of coated hot buffer filler strips generally showed favorable results for inhibiting core surface corrosion; not by producing hydrocarbons but by minimizing the hydrogen gas supplied to the filler gap through a tortuous radial inflow path. The coating acting as a protective barrier to prevent forming of self-generating corrosion flow paths between tile gaps and filler gaps.
3. The spring loaded core model showed promising results as the model lateral support system although the springs utilized did take on a permanent set during the test.

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2.0 TEST MODEL

The basic test configuration consists of a 6.0 inch diameter model 47 inches long which includes a 3.5 inch diameter core assembly, a simulated reflector with a simulated NRX-A2 type lateral support and seal system.

An isometric cutaway illustration of the test model is shown in Figure 1. Also included in Appendix A of this report are the general assembly drawings of the model and detail drawings of each component part.

In this test model, the principal component to be evaluated under operating test conditions was the hot buffer type core assembly. This core assembly consists of an uncoated inner core surrounded by twelve hot buffer filler strips and twelve full length insulating tile. The hot end view of the core assembled is shown in Figure 2. The particular photograph shown in Figure 2 was taken after the first hot hydrogen flow test.

Material for each of the components were specially selected to meet the test requirements. In critical peripheral areas; i. e., filler strips and insulating tile, the material selected duplicated the same grade as specified in the reactor. The inner core which simulates the reactor core was made from non-fueled grade HLM-85 graphite. This grade of graphite closely simulates the material properties of the current fuel element material. The various grades of graphite incorporated in the model are summarized in Table I.

There follows a discussion of the principal components used in the Hot Buffer Component Test Model.

2.1 CORE ASSEMBLY

The core assembly consists of an uncoated inner core, full-length simulated hot buffer type filler strips, and full length insulating tiles.

2.1.1 Inner Core

The outer surface of the inner core, which was purposely left uncoated for this test, is machined to represent the periphery of a regular cluster assembly. The inner core was made hollow in the center to accommodate a graphite heater element.

A trial attempt to reduce the gas permeability through the wall was made by coating the inner wall of the core with National Carbon C-14 cement. However, only the first stage cycle in curing the cement could be performed. The first stage cycle specifies heat curing from room temperature to $260 \pm 10^{\circ}\text{F}$ at a uniform rate of $15 \pm 5^{\circ}\text{F}$ per hour in air. The second stage cycle which was unable to be completed because of scheduled reactor commitments specifies heat curing at $1600 \pm 25^{\circ}\text{F}$ in dry argon or helium at a rate not exceeding $120 \pm 10^{\circ}\text{F}$ per hour, followed by furnace cooling to room temperature.

2.1.2 Filler Strips

Full-length simulated hot buffer type filler strips were specially designed and were made from reactor grade Graphitite "G" filler strip material. Twelve single section filler strips 47 inches long surrounded the core. Six of the filler strips were uncoated and six were specified to be coated one-mil thick with zirconium carbide (ZrC). The coating which existed only on the peripheral chord surface of the filler strip extended from about the 9.0 inch axial core station to the 47 inch core station.

2.1.3 Insulating Tile

Full-length simulated hot buffer insulating tiles were specially designed to accommodate a 3.5 inch diameter core and were made from rejected reactor grade raw material. Manufacturing information for the insulating tile is summarized in Table II.

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To facilitate adapting to the small diameter core, the outside periphery of the insulating tile was machined to 1.75 inch reference radius. The base of the tile was machined flat to adapt to the filler strips. Maximum nominal thickness of the tile was 0.185 inches and occurred at mid-chord and decreased along an arc to a thickness of 0.125 inch at each end. Detail drawings of tile are included in Appendix A.

2.1.4 Special Core Fitting Procedures

In order to obtain representative values for filler gaps and tile gaps, a special method was employed where successive fitting, measuring, and machining operations were utilized. This method first requires the availability of excess stock on the surfaces to be machined. To provide this excess stock, the lobes of the inner core were purposely machined 1/16 inch oversized during the first stage machining operation. By fitting selected filler strips, i. e., two V-type and one flat bottom type, a base nominal filler strip gap was determined by averaging the measured values between the filler strips. After establishing the average base filler gap value, the first machining cut was made. The amount of material selected to be removed on the first cut made, depended on the base gap measured and the estimated amount of excess stock available. After the first cut the filler strips were fitted to the core and the gaps were remeasured. Successive machining operations followed in the same manner until the stepping gap between the adjacent V-type filler strips and the flat bottom type filler strip measured zero. Once the stepping gap was established the final filler strip gap was measured and if it fell within the nominal value required, the machining operation was completed. If the measured gap was not within the nominal value, the V-slots of the inner core or the filler strips had to be re-machined. For this particular core, all the values were within the nominal expected values.

2.2 LATERAL SUPPORT AND SEAL SYSTEM

To improve on the earlier model design which included a felt cushion lateral support system, a specially designed solid reflector was made which utilized a spring loaded lateral support system.

The lateral support and seal system in the Build 4 Test 1 model utilized seventeen rows of segmented seal rings which employed only V-grooved backed NRX-A2 type seal segments.

The inner surfaces of the seal segments were grooved to provide axial flow channels. There were a total of twelve flow channels per segmented seal ring, equivalent to one flow channel per insulating tile. The flow channels had a uniform width and were distributed such that each groove spanned a filler strip gap and each land spanned a tile gap. The depth of the flow channels in each row of seal segments were scheduled to provide a variable axial pressure distribution. Table III tabulates the seal schedule used for this test.

The core was bundled by utilizing coil springs to mechanically load the seal segments. Each seal ring in the lateral support system had three segments and each segment was spring loaded by two coil spring-plunger cylinder assemblies. The coil springs used had a spring rate of 73 lbs/in. The springs were designed to exert a six pound nominal pre-load force per pin. This force resulted in a cold pre-load bundling pressure of approximately 1.2 psi based on total peripheral core area or 2.2 psi based on total seal ring contact area.

2.3 SIMULATED REFLECTOR (CYLINDER ASSEMBLY)

A specially designed solid reflector was fabricated with threaded holes located circumferential around the periphery to incorporate installation of the plunger pin assemblies.

The outside surface of the reflector was coated with a 10-mil thick zirconium oxide (ZrO_2) coating in an attempt to reduce the wall permeability. However, preliminary permeability checks showed that the plasma spraying technique used in coating the reflector did not effectively reduce the permeability. In a trial attempt to improve on the sealing capabilities of the coating, Glyptal and National Carbon C-14 cement were painted over the ZrO_2 coating. Glyptal was painted on the cold end portion of the reflector and extended from core station 3 to 14 inches. C-14 cement was painted from about 14 to 42 inches and air dried. Five inches of unpainted ZrO_2 coating was provided at the hot end to allow model clearance through the hot end chuck during furnace installation. A post test photograph of the reflector is shown in Figure 3 which shows the deteriorated condition of the C-14 cement along the mid core section. The results show that curing the cement at temperature is essential to prevent deterioration.

2.4 HEATER ELEMENT

A specially designed tapered resistance heater element was fabricated for the Build 4 Test 1 model. The heater element was designed to produce local temperature levels which are representative of the maximum operating temperature levels of current reactor peripheries. During operation, heat is transferred by thermal radiation from the surface of the heater element to the inner wall of the core. The core components, i. e., inner core, filler strips, and insulating tile, are heated by conduction. The resistance heater element was 56 inches long and was made from a rod of Graphitite "G" graphite. During the hot hydrogen flow tests the surface of the heater element is protected by providing a helium gas environment in the plenum between the heater and the wall of the inner core. The flow through this plenum is maintained at a minimum leakage level and is controlled by a deep hole drilled opening in the hot end pyro plug. Detailed information on the design of the heater is described in Appendix C.

3.0 ASSEMBLY MEASUREMENTS

Assembly measurements, including pertinent dimensional and weight measurements of the components before and after test, are included in Appendix A. Thickness gauges, micrometers, and comparators were used where applicable to measure the required assembly measurements.

4.0 INSTRUMENTATION

Parameters measured, in addition to those required for operating the A-10 Single Cluster Furnace, included: pressure, temperature, and power measurements. A complete list of the instrumentation together with their location is summarized in Table IV.

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5.0 TEST PROCEDURE

The operational procedure used for the HHT-7 model test is the same as that adopted by the Fluid Flow Laboratory for the operation of the A-10 Single Cluster Test. In general, high pressure hydrogen gas supplied from tube trailers enters the furnace and flows vertically downward through the core interstices where the gas is heated to a specified temperature condition. A flow schematic illustrating the paths through the test apparatus is shown in Figure 4.

To establish trade-off operating conditions for the model, preliminary functionally checkout tests with ambient hydrogen and heated helium were conducted before proceeding with the hot hydrogen flow tests. These preliminary tests include a heater element performance test, a cold hydrogen flow test, and a hot helium flow test at intermediate power levels. The results of these tests are described in Appendix C.

Through these functional checkout tests, just enough data is obtained to establish general model operating characteristics, i. e., flow, pressure, and temperature data at off power and intermediate power conditions. Data from these tests are extrapolated to estimate the operating conditions for the hot hydrogen flow tests.

The purpose of these tests is to utilize the extrapolated data in establishing the best trade-off conditions between the operating temperature level, pressure drop, and flow rate to maximize the duration of the model test.

To maximize the duration of the model tests requires increasing the life of the heater element by reducing the surface to centerline temperature gradient without decreasing the heater surface temperature. This gradient was reduced by lowering the operational power level. In order to lower the power level and maintain the same inner core temperatures, the flow through the seal system was decreased. This decrease in flow rate resulted in an increase in operating temperature of the reflector wall.

Utilizing the extrapolated data, the best trade-off condition between the operating power level, flow rate, and temperature was established. The tests are then conducted under these established trade-off conditions until the heater element fails or the required test duration is satisfied. At which time the test is terminated.

After establishing the specified hydrogen flow rate through the model at the required exit pressure condition, power is then imposed to the heater element at a step-up ramp rate which is compatible with the system. Once the specified power level is reached the test is continued uninterrupted until a heater element failure or duration time terminates the test.

6.0 EXPERIMENTAL LIMITATIONS

The primary factor which limited the test operation of the Build 4 Test 1 model was the life capability of the heater element. As a result of this limiting capability, the test objectives to provide experimental data for two 20 minute corrosion run cycles were not achieved. Instead of two 20 minute run cycles, two shorter duration tests of 19 and 9 minutes were conducted. Corrosion results from these shorter duration tests are presented herein.

7.0 EXPERIMENTAL RESULTS

Both hot hydrogen flow tests (HHT-7-4-1-HH2-1 and 2) were conducted utilizing the extrapolated information from the preliminary functional checkout tests. Each of the flow tests failed to meet their expected test objective of operating at corrosion temperature levels for a 20 minute test duration and both tests were terminated as a result of a heater element failure. A summary of each of these tests follows.

7.1 BUILD 4 TEST 1 - TEST NUMBERS HHT-7-4-1-HH2-1 AND 2

From the results of the heater element performance test, the cold hydrogen flow test, and the hot helium flow test, the power level and flow rate for the hot hydrogen tests were specified. Power level-heater temperature limitations established during the functional checkout tests prevented matching of the flow rate, temperature, and pressure conditions of the model with those simulating the reactor.

The first of the two tests operated at the specified power level of 130 KW for a duration of 19 minutes including a transient heat-up time, 14 minutes at local core temperature levels in excess of 3000°R. Pressure drop across the furnace varied throughout the test; starting at 41 psi, increasing to 138 psi after 6 minutes of testing, and decreasing back to 40 psi at the end of the power test. The model pressure drop, Figure 6b, not only varied with the temperature rise of the gas flowing through the seal and interstitial flow system but also with operating changes in establishing flow conditions.

From the flow data presented in Figure 6a, it appears that the internal helium leakage has the greatest influence in perturbing the pressure drop. This perturbation was attributed to the gradual rate of increase of helium flow through the reflector wall due to the deterioration of the coating. Operating changes to reduce the internal helium leakage and maintain the prescribed helium-hydrogen differential control pressure resulted in the decrease in model pressure drop. Back pressure was maintained at

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approximately 564 psia at an approximate hydrogen flow rate of 0.025 lb/sec. Figures 5 and 6, respectively, show the power-temperature-time history and pressure-flow-time history of the test. Figure 7 shows measured temperature levels recorded at different times during the test and are compared with the design axial distributions.

The second test operated at the specified power level of 130 KW for a duration of only nine minutes including a transient heat-up time. Maximum core temperature measured was 2860°R. Pressure drop across the model varied from 20 to 65 psi with constant back pressure of approximately 550 psig and constant flow rate of 0.025 lb/sec.

Figures 8 and 9, respectively, show the power-temperature-time history and pressure-flow-time history of this test.

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8.0 DISCUSSION OF RESULTS AND PRELIMINARY CONCLUSIONS

Utilizing the apparatus and method of test previously described, two hot hydrogen flow tests were performed to provide preliminary experimental information on the general type of corrosion behavior which can be expected in a hot buffer type peripheral design. Data from the two hot hydrogen flow tests, HHT-7-4-1-HH2-1 and 2, are summarized in Tables V and VI, respectively.

The discussion of the results reported herein will be directed to:

1. presenting only the experimental information, and
2. providing information on the model, the test method or the environmental conditions where necessary to help in explaining the corrosion behavior produced.

The results of the model tests yielded the following qualitative corrosion characteristics along the core surface where temperature levels were high enough to produce corrosion.

1. Hydrogen exposed surfaces of both the coated and uncoated filler strips and the core showed various degrees of regression, with the degree of regression on the coated surfaces depending primarily on pre-test condition of the coating.
2. Incipient to no surface regression existed on the core surface under the sector of coated filler strips, in contrast to the relatively heavy corrosion patterns that existed under the sector of uncoated filler strips.
3. Wide corrosion areas with relatively light surface regression patterns existed on the peripheral chord face of the uncoated filler strips, in contrast to the narrow line-crater type corrosion with relatively deep surface regression patterns produced on the peripheral chord face of the coated filler strips.
4. Recurrent corrosion patterns were produced on the peripheral chord face of the filler strips and were primarily attributed to the presence of seal segments which directed the flow from the seal cavities inwards toward the core surface.

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5. In general, the radial surface of the uncoated filler strips showed a relatively higher degree of surface regression in contrast to the coated filler strips. This behavior was primarily attributed to the communication passage produced across the chord face of the filler strip through progression hydrogen-graphite corrosion reactions. The hydrogen exposed uncoated surfaces being more susceptible to corrosion.
 6. Corrosion patterns on the bottom land surface of the filler strips were approximate mirror images of the pattern produced on the hydrogen exposed peripheral surfaces of the core.
- Artist schematics showing representative regression measurements are presented in Figures A-18 through A-41 in Appendix A.

A brief description of the corrosion pattern produced on the hydrogen exposed surfaces of each of the principal test components follows.

8.1 INNER CORE CORROSION

In the hot buffer model test, the corrosion produced on the peripheral core surface under the sector of uncoated filler strips was primarily attributed to a communication path which existed between the seal cavities in the lateral support and seal system and the core surface. This communication path was made possible by a progressive hydrogen-graphite corrosion reaction that progressed with time along the chord face of the uncoated filler strip, until a path was formed between the tile gap and filler strip gap. Once the path extended from the tile gap to the filler strip gap, a fresh supply of hydrogen was readily available to enter the tile gap, flow along the new formed passages, and dump into the radial filler strip gap attacking the core surface.

The flow-corrosion behavior described above is more likely to occur with the uncoated filler strips than with the coated filler strips because of uncoated peripheral chord surface being more susceptible to corrosion. If this surface is protected, e. g. , by a coating, the hydrogen gas entering the tile gap must first break down the coating

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before it can attack the graphite. Until the coating fails, the hydrogen gas entering the tile gap is forced to flow axially along the tile gap with the probability of resulting in a narrower type corrosion pattern along the tile gap. This axial flow behavior would produce corrosion that is localized but relatively more severe. If the coating withstands the hydrogen attack, less core surface corrosion would be expected to exist under the sector of coated filler strips. This conclusion is compatible with the results obtained from the test. Post test photographs of both the core and the filler strips illustrating this effect are shown in Figures 10 through 15.

A discussion describing the post test condition of the core surfaces follows.

8.1.1 Surface Under the Sector Incorporating the ZrC Coated Filler Strips

No corrosion existed on the core surface under the sector of ZrC coated filler strips with the exception of incipient traces under filler strips where the coating failed. Corrosion was found to exist on the core surface only where temperatures were high enough to sustain hydrogen-graphite reaction. For example, in Figure 12C, traces of incipient corrosion were found to exist on the core surfaces F-5CL and F-5CR from about the 37 to 40 inch core stations. Correspondingly shown in Figure 12B at the same axial station where the coating quality was apparently poor, a corrosion path existed from mid-chord to the edge. This path allowed limited flow to communicate between the tile gap and filler strip gap, thereby producing some core surface corrosion. Measured corrosion depths across the peripheral chord face ranged from approximately 30 mils at the tile gap and tapered to about 5 mils at the filler strip gaps. Detailed artist sketches of the surface corrosion patterns with estimated surface regression depths are schematically represented in Figures A-18 through A-41 in Appendix A.

8.1.2 Surface Under the Sector Incorporating the Uncoated Filler Strips

Relatively heavy corrosion patterns existed under the sector of uncoated filler strips. This heavy corrosion behavior was traced to the communication path formed between the seal cavity plenums and the core surface via the tile and filler strip gaps. This path was attributed to the heavy corrosion which was produced along the chord surface of the filler strip. For example in Figure 14E, heavy corrosion patterns were observed on core surfaces F-9CL and F-9CR from about the 33 to 40-1/2 inch core stations. Correspondingly at about the same axial station, Figure 13D, the corrosion path on both filler strips F-8 and F-9 extends from the tile gap region to the filler strip gap.

8.1.3 Other Unusual Behavior

In addition to some deposition resulting from upstream corrosion behavior, an unusual large amount of unexplained deposition-plating-deposition phenomena occurred from the 19 to 28 inch axial core stations on both the core surfaces, F-9CL and F-9CR, and on the adjacent filler strip surface, F-9C. This deposition was strikingly darker in contrast to the other deposits noted. Figures 13C and 14C shows the deposition in question. Because of the contrastingly different texture of this deposit it was felt that it was something other than soot deposit resulting from corrosion. One logical explanation is to identify the deposition as decomposed residue from the monofilament nylon fishing line, or acetate tape which was used to facilitate installation of the core assembly into the reflector. Figures 13B, 13E, and 14B show pre-test photographs, locating the fishing line and tape relative to the core station.

8.2 FILLER STRIP CORROSION

The two test sectors of filler strips, coated and uncoated, utilized in the model yielded different types of corrosion results on the peripheral chord surfaces. The results showed

that the corrosion pattern on the peripheral chord surface of the coated filler strips were localized and confined to the tile gap region. In contrast, the uncoated filler strips showed wide area type corrosion which spread across the chord face and in certain areas progressed as far as the filler strip gap. This wide area type corrosion was also evident on coated filler strips that were suspected to have a coating with relatively poor adhering qualities.

The primary reason for the difference in the corrosion results was traced to the effectiveness of the coating on the peripheral chord surface of the filler strips. The test results show that where the coating appeared to be relatively good and adhered properly to the filler strips, the filler strip surface was satisfactorily protected. The technique used to coat the filler strips with ZrC for this particular build was still in the early experimental stages of development. A brief history of developments which occurred during coating of the filler strips is discussed in Appendix C in order to explain some of the peculiarities associated with this particular coating phase. Also, included in Appendix C are test results from a single channel isothermal test sample which support the conclusion that the effectiveness of the ZrC coating depends primarily on its ability to adhere to the surface.

Reasons, other than coating effectiveness, that need to be considered in evaluating the contrastingly different corrosion patterns are discussed below.

1. Core Bundling. Because of the operating temperature level at which the stainless steel lateral support springs were subjected to, the springs at some point in the test had taken a permanent set. Figure 16 shows the results of this behavior. Due to the uncertainty in the effectiveness of the core bundling pressure, undefined axial flow gaps between the filler strip and core could have existed. However, if radial expansion of the component parts were large enough and the axial pressure distribution maintained, sufficient preload bundling force could be generated to maintain

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a relatively good surface to surface fit on all components. In contrast, if this force is not sufficient enough, a narrow axial flow gap under the filler strip could exist. If the latter behavior is true, this gap should exist under both sectors, resulting in a symmetrical flow pattern and in turn produce identical core surface corrosion under both the coated and uncoated sectors of filler strips. Since the core surface corrosion patterns between sectors were unmistakably different, the contribution of the spring failure in influencing corrosion behavior appeared to be small.

2. Non-Uniform Flow Area Gap. If the flow area at each of the filler strip or tile gap varies because of dimensional tolerances, the flow in each parallel channel will vary in proportion to the pressure drop and temperature conditions established across the actual gap. This flow variation could produce unsymmetrical radial pressure and temperature gradients which could result in a non-uniform corrosion pattern.

There follows a description of the surface regression patterns observed on each of the filler strip surfaces. The code letters and nomenclatures utilized to identify these surfaces are illustrated in the sketch on Page 19.

8.2.1 Peripheral Chord Surface of the Filler Strip (Surface A)

The corrosion pattern on the peripheral filler strip surface, i. e., the surface, adjacent to the tile, is illustrated in the post test photographs, Figures 17 through 21.

Figure 17 shows the peripheral chord surfaces of the filler strips comparing the corrosion pattern on the coated and uncoated surfaces. In addition, the overall view of the coated filler strip, Figure 11A, is included to show the comparison of the pre test condition of the coated surfaces with the post test corrosion results.

VIEW LOOKING UPSTREAM

Figures 18 through 21 show enlarged sections of the uncoated and coated filler strips showing typical corrosion patterns along the axial length. Superimposed on the photographs are identification markers locating each row of seal segments in proper orientation to the respective filler strip stations. Note that the corrosion patterns corresponds closely with the seal segment markers illustrating the radial inflow effect produced from the presence of seal segments in the lateral support and seal system even though no large radial pressure gradient exists in the model.

8.2.2 Filler Strip Radial Faces (Surfaces B and D)

Some corrosion, deposition, and plating was noted to exist on the radial faces of both the coated and uncoated filler strips. Figures 22 through 25 show post test photographs of the radial faces and the resulting effect produced on these surfaces.

In most cases the surface regression was more severe on the radial faces of the uncoated filler strips. Corrosion areas, in some cases, extended from the 26 to the 41 inch core stations. A typical example of this behavior is illustrated on filler strip surfaces F-12B in Figure 23A.

Some deposition and plating was noted on the radial faces of both the coated and uncoated filler strips, although it appeared to be more clearly defined on the uncoated type. Some of the thicker deposits were approximated to range in thickness up to one mil. This deposition-plating behavior is illustrated in Figure 23 on filler strip surfaces F-4B, 5B, 10B, and 11B. Generally most of the deposition-plating effect appeared to be concentrated only in the area around the 42 inch core station.

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On both the coated and uncoated filler strip sectors, isolated cases of corrosion on the radial faces indicated an axial-radial type of flow behavior. This behavior indicated that hydrogen entered the filler strip gap under an inflow component, producing the corrosion and deposition. This behavior can best be visualized using the sketch on Page 22 and utilizing the following assumptions.

1. Hydrogen gas enters the core through the annulus upstream of the first seal segment with the flow in the filler strip and tile gaps being axial.
2. The flow streamlines in the tile gap remain axial between each row of seal segments, but because of the presence of the restricting flow area in the seal rings the flow is diverted and accelerated inwards toward the core. The accelerated axial-radial velocity components forces the flow inwards through the tile gap. As a result of this accelerated flow behavior the peripheral surface of the filler strip under each row of seal segments would be more susceptible to corrosion. This corrosion can be localized (e. g., by coating the surface) or permitted to spread out across the peripheral chord face as observed on the uncoated surfaces to form a communication path towards the filler strip gap.
3. If no communication passage exists between the tile gap and filler strip gap along the peripheral chord face of the filler strip, the flow streamlines in the filler strip gap are axial. However, once a communication passage is established (e. g., by corrosion), the axial-radial streamline velocity component forces the flow inwards through the tile gap with the potential of diffusing across the chord to the filler strip gap or flowing axially down through the tile gap into the next seal cavity. If this behavior exists, the core surface is more susceptible to corrosion. A typical example of this behavior is illustrated on the radial face of filler strips F-6B, 11B, and 12B in Figure 23. The corrosion pattern illustrates the axial-radial flow sweeping in and out at about the 26 to the 31 inch core stations; F-6 being a coated filler strip and F-11 and F-12 being uncoated.

8.2.3 Bottom Land Surface of Filler Strip (Surface C)

The bottom land surfaces of the coated filler strips showed traces of incipient to no corrosion with some local deposition. These surfaces are presented in Figures 26 and 27.

The bottom land surface of the uncoated filler strips showed corrosion patterns that were approximately mirror images of the core surface corrosion patterns. These filler strips are presented in Figure 26. The corrosion on these surfaces were wide band type and existed from about the 34 inch to the 40 inch core stations. In addition to the normal expected deposition area associated with corrosion, a strikingly contrastingly different deposition-plating-deposition area was produced, Figure 26A, from about the 28 to the 33 inch core stations which was the mirror image of the core deposition. This behavior pattern was discussed previously in the section on Inner Core Corrosion.

8.3 INSULATING TILE CORROSION

The hot buffer tile utilized in the model test showed that incipient to no corrosion existed on both the core peripheral surface adjacent to the filler strip. However, edge corrosion on the radial faces of the tile gaps was common and existed from about the mid-core to the exit core station. In addition to tile edge corrosion, deposits on the surface adjacent to filler strips were noted. These deposits were approximate mirror images of the pattern obtained on the peripheral chord face of the filler strips. There follows a description of the corrosion behavior on each of the tile faces.

8.3.1 Peripheral Chord Surface (Surface A)

Recurrent circumferential discoloration bands along the axial length were found on the seal segment seating surface of the tile. These bands are shown in

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Figures 28 and 29 and match identically to spacing between each row of seal segments. In addition, discoloration paths are visible showing the channel flow path identifying the seal segment flow slots.

These discoloration markings imply that the seal segments were seated properly against the face of the tile during the test.

In addition to the discoloration bands, residue from the acetate tape and nylon fishing line were found. From the residue that remained it was apparent that the fishing line had become untied during assembly and became captured between the seal segment and tile surface. Since the temperature level in this area was not high enough to cause complete decomposition, the nylon line merely softened sufficiently to adhere to the surface during cool-down. Remains of the fishing line are identifiable on Figures 28 and 29.

8.3.2 Radial Edge Faces (Surfaces B and D)

Both corrosion and deposition were noted to exist along the edge faces of the tile. Figures 30 and 31 show post test photographs of the hot end edge section of the tile. Corrosion depths up to 14 mils were measured.

8.3.3 Bottom Land Face (Surface C)

No measurable signs of corrosion were noted on the tile-filler strip interface surface; however, extensive deposits were found which were mirror images of the pattern produced on the peripheral chord face of the filler strips. Figure 32 shows the hot end section of the tile and the deposition pattern produced. In some cases axial lines corresponding to the filler strip gap is clearly identifiable.

8.4 SEGMENTED SEAL RING

No measurable traces of corrosion were found on the surfaces of the seal segments.

Figure 33 shows selected rows of seal rings which typically represents the post test condition of the surfaces. Deposition on the lands of the seal segments identify the tile gap. Chipped edges and corners seen on the seal segments occurred during the disassembly.

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RECOMMENDATIONS

The advancements gained through the development and testing of each of the experimental models promisingly suggests a wider application in the use of the basic configuration.

Recommended examples of some of these applications are: (1) combining the single cluster test configuration with the reflector and lateral support and seal system design, (2) utilizing the results of the tests to establish an analytical model which would reproduce the test results, (3) utilizing the analytical test model to predict the behavior of proposed core designs, (4) repeating model tests where necessary to ascertain confidence in the analytical predictions, (5) applying the model information to evaluate reactor periphery and core designs, and (6) developing heater design technology to provide a reliable high temperature heater element with the capability of operating for a duration of one hour or longer.

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Table I
Component Material List

<u>Part Description</u>	<u>Graphite Grade</u>
Reflector	H4LM
Inner Core	HLM-85
Filler Strips	Graphitite "G"
Heater Rod	Graphitite "G"
Seal Segments	See Table III

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Table II
Insulating Material Manufacturing Information

Model Identification Number	Manufacturing Information			
	Purchase Order Number	Serial Number	Lot Number	Identification Number
T-1	49811	4	1703	73-16-1
T-2	49811	7	1703	73-16-1
T-3	49811	6	1703	73-16-1
T-4	49811	29	1779	73-20-3
T-5	49811	14	1703	73-16-C3
T-6	49811	8	1719	73-20-4
T-7	49811	21	1779	73-20-3
T-8	49811	20	1779	73-20-3
T-9	49811	30	1779	73-20-3
T-10	49811	28	1779	73-20-3
T-11	49811	5	1719	73-20-4
T-12	49811	19	1703	73-16-C3

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Table III
Seal Segment Flow Slot Depth Schedule

Seal Ring Number	Nominal Flow Slot Depth - Mils	Grade of Graphite Material
1	11	ATJ
2	11	ATJ
3	11	ATJ
4	11	ATJ
5	11	ATJ, ZTA
6	9	ATJ
7	9	ATJ
8	9	ATJ
9	9	ATJ
10	9	ZTA
11	7	ATJ
12	7	ATJ
13	7	ATJ
14	7	ATJ
15	7	ATJ
16	50	ATJ
17	7	ATJ

Seal Segment R-5-SS2 fabricated from ZTA.

Seal Ring 16 is considered an ineffective seal ring.

Table IV
HHT-7 Build 4 Test 1 Instrumentation Summary

Instrumentation Number	Type	Recorder Range	Location
				Axial Location (Inches)	Angular Location (Degrees)
<u>Temperature</u>					
T0	Chromel-Alumel Thermocouple	- 320 to 2000°F	Hydrogen Inlet Line		
T1	Chromel-Alumel Thermocouple	- 320 to 2000°F	Upper Chuck Plenum	- 2.50	300
T2	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Material	8.03	15
T3	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Gas	8.03	45
T4	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Material	13.7	75
T5	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Material	24.9	135
T6	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Material	30.5	195
T7	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Gas	30.5	225
T8	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Material	33.4	255
T9	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Material	41.8	315
T10	Chromel-Alumel Thermocouple	- 320 to 2000°F	Reflector Gas	41.8	345
T11	Chromel-Alumel Thermocouple	0 to 50 MV	Innercore Material	6.5	30
T12	Chromel-Alumel Thermocouple	0 to 50 MV	Innercore Material	14.4	80
T13	Tungsten/Tungsten-26% Rhenium	0 to 50 MV	Innercore Material	24.5	50
T14	Tungsten/Tungsten-26% Rhenium	0 to 50 MV	Innercore Material	30.3	21.0
T15	Tungsten/Tungsten-26% Rhenium	0 to 50 MV	Innercore Material	30.3	2.70
T16	Tungsten/Tungsten-26% Rhenium	0 to 50 MV	Innercore Material	41.5	330
<u>Pressure</u>					
P1	Gage	0 - 1000 psig	Furnace Inlet		
P2	Gage and Moore Recorder Controller	0 - 1000 psig	Furnace Outlet		
P3	Transducer	0 - 1000 psig	Seal Cavity	13.7	100
P4	Transducer	0 - 1000 psig	Seal Cavity	27.5	165
P5	Transducer	0 - 1000 psig	Seal Cavity	41.8	285
DP(1-2)	Gage and Moore Recorder Controller	0 - 250 psi	Furnace Pressure Drop		

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Table IV (Continued)

Instrumentation Number	Type	Recorder Range	Location	Axial Location (Inches)	Angular Location (Degrees)
<u>Flow</u>					
m1	Orifice (d = 0.367 Inch)	0 - 100 inches of H ₂ O	Hydrogen Supply		
m2	Orifice (d = 0.186 Inch)	0 - 100 inches of H ₂ O	Helium Atmosphere Supply		
m3	Orifice (d = 0.120 Inch)	0 - 100 inches of H ₂ O	Heater Atmosphere Supply		
m4	Orifice (d = 0.161 Inch)	0 - 100 inches of H ₂ O	View Port No. 5 Coolant		
<u>Power</u>					
E1	Voltmeter and Millivolt Recorder	0-250 V and 0 - 100 MV			
I1	Millivolt Recorder	0 - 10 MV			

1 Model inlet face reference as zero core station.

2 Clockwise looking downstream.

Table V

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Summary of Measured Data From Hot Hydrogen Flow Test, HHT-7-4-1-HH2-1

Instrumentation Number	Time: t = 17 Minutes
<u>Temperature - °F</u>	
T0	50
T1	172
T2	433
T3	430
T4	612
T5	963
T6	1129
T7	988
T8	1183
T9	1185
T10	1150
T11	1547
T12	X
T13	3040
T14	X
T15	3770
T16	3885
<u>Pressure - psia</u>	
P1	615
P2	564
P3	606
P4	601
P5	X
DP(1-2)	51
<u>Flow Rate - lb/sec</u>	
$\dot{m}_1$	.0240
$\dot{m}_2$	.0069
$\dot{m}_3$	.0004
$\dot{m}_4$	.0023
<u>Power</u>	
EI - volt	70
II - amperes	1873
P - kilowatt	131

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Table VI

Summary of Measured Data From Hot Hydrogen Flow Test, HHT-7-4-1-HH2-2

Instrumentation		Time: t = 12 Minutes
Number		
<u>Temperature - °F</u>		
	T0	48
	T1	80
	T2	215
	T3	215
	T4	332
	T5	610
	T6	672
	T7	485
	T8	714
	T9	644
	T10	572
	T11	1099
	T12	1300
	T13	2300
	T14	X
	T15	2400
	T16	X
	<u>Pressure - psia</u>	
	P1	670
	P2	564
	P3	654
	P4	618
1	P5	X
	DP(1-2)	106
	<u>Flow Rate - lb/sec</u>	
	m1	.0251
	m2	.0136
	m3	.0006
	m4	.0022
	<u>Power</u>	
	EI	70
	II	1890
	P	132

1

Post test inspection showed sensor probe leak.

Post test
inspection
showed
sensor
probe
leak.

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Figure 1

Six-Inch Diameter Hot Buffer Filler Strip Corrosion Test Model

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Figure 2

Hot End View of HHT-7 Build 4 Test 1 Hot Buffer Periphery Test Model

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Figure 3
Post Test Photograph of Reflector Coating Condition

Figure 4

A-10 Cluster Furnace Flow System
 Showing Representative Internal Flow Paths of HHT-7 Model

Figure 5

Power-Temperature-Time History of Test HHT-7-4-1-HH2-1

Figure 6

Pressure-Flow-Time History of Test HHT-7-4-1-HH2-1

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Figure 7
 Axial Temperature Distribution From Test HHT-7-4-1-HH2-1

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Figure 8

Power-Temperature-Time History of Test HHT-7-4-1-HH2-2

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Figure 9

Pressure-Flow-Time History of Test HHT-7-4-1-HH2-2

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10a FILLER STRIP

10b FILLER STRIP

10c INNER CORE

Figure 10

Post Test Photographs Showing the Comparison Between the Peripheral Surface
of the Coated Filler Strip Sector With the Adjacent Inner Core Surface

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Figure 11

Post Test Photographs Showing the Comparison Between the Peripheral Surface
of the Coated Filler Strip Sector With the Adjacent Inner Core Surface

12a FILLER STRIP

12b FILLER STRIP

12c INNER CORE

Figure 12

Post Test Photographs Showing the Comparison Between the Peripheral Surface
of the Filler Strips With the Adjacent Inner Core Surface

Figure 13

Post Test Photographs Showing the Comparison Between the Peripheral Surface of the Uncoated Filler Strip Sector With the Adjacent Inner Core Surface

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Figure 14

Post Test Photographs Showing the Comparison Between the Peripheral Surface
of the Uncoated Filler Strip Sector With the Adjacent Inner Core Surface

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15a FILLER STRIP

15b FILLER STRIP

15c INNER CORE

Figure 15

Post Test Photographs Showing the Comparison Between the Peripheral Surface
of the Filler Strips With the Adjacent Inner Core Surface

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Figure 16

Difference Between the Pre and Post Test
Free Length Measurement of Lateral Support Springs

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Figure 17

Post Test Photographs of Uncoated Filler Strip Surfaces
Peripheral Chord Face of Hot Buffer Filler Strips

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18a

18b

Figure 18

Post Test Photographs Showing Corrosion Behavior
on the Peripheral Chord Surfaces of the Coated and Uncoated Filler Strips

Post Test Photographs Showing the Corrosion Behavior
on the Peripheral Chord Surfaces of the Coated and Uncoated Filler Strips

Figure 19

NOTE: FILLER STRIP PHOTOGRAPHED WITH FOLDING RULE REVERSED
20a

Figure 20

Post Test Photographs Showing the Corrosion Behavior
on the Peripheral Chord Surfaces of the Coated and Uncoated Filler Strips

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Figure 21

Post Test Photographs Showing the Corrosion Behavior Produced
on the Peripheral Chord Surfaces of the Coated and Uncoated Filler Strips

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22a

22b

Figure 22

Post Test Photographs Showing the Corrosion Behavior Produced
on the Radial Surface (B) of the Coated and Uncoated Sector of Filler Strips

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23a

23b

Figure 23

Post Test Photographs Showing the Corrosion Behavior Produced
on the Radial Surface (B) of the Coated and Uncoated Filler Strips

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Figure 24

Post Test Photographs Showing the Corrosion Behavior Produced
on the Radial Surface (D) of the Coated and Uncoated Filler Strips

Figure 25

Post Test Photographs Showing the Corrosion Behavior Produced
on the Radial Surface (D) of the Coated and Uncoated Filler Strips

Figure 26

Post Test Photographs Showing the Corrosion Behavior
on the Bottom Land Surface (C) of the Coated and Uncoated Filler Strips

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Figure 27

Post Test Photographs Showing Corrosion Behavior
on the Bottom Land Surface (C) of the Coated and Uncoated Filler Strips

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Figure 28

Post Test Photographs of Insulating Tile

29a - PERIPHERAL CHORD FACE - UNCOATED SECTOR

29b - PERIPHERAL CHORD FACE - COATED SECTOR

Figure 29

Photographs Showing the Post Test Condition of the
Peripheral Chord Face of the Hot Buffer Type Insulating Tile

Figure 30

Photographs Showing the Post Test Condition of the
Radial Edge Face (B) of the Hot Buffer Type Insulating Tile

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31a - RADIAL FACE "D", UNCOATED SECTOR

31b - RADIAL FACE "D", COATED SECTOR

Figure 31

Photographs Showing the Post Test Condition of the
Radial Edge Face (D) of the Hot Buffer Type Insulating Tile

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32a - FILLER STRIP - TILE INTERFACE SURFACE - UNCOATED SECTOR

32b - FILLER STRIP - TILE INTERFACE SURFACE - COATED SECTOR

Figure 32

Photographs Showing the Post Test Condition of the
Bottom Land Surface (C) of the Hot Buffer Insulating Tile

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Figure 33

Photographs Showing Representative Post Test Condition of Seal Segments

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APPENDIX A DIMENSIONAL MEASUREMENTS

The assembly drawing of the Build 4 Test 1 model and detail drawings of the components are presented in Figures A-4 through A-15 for quick reference in establishing model dimensions. Nominal dimensions shown on the drawings can be used where applicable. In addition to the drawing dimensions, a dimensional inspection of the seal segment groove sizes, gaps between filler strips, and radial stepping gaps were performed on the model to approximate their respective flow areas. A concise description of measurements made before and after assembly is discussed below.

SEAL SEGMENT DIMENSIONAL MEASUREMENTS

A dimensional inspection of the seal segment grooves was performed to obtain an approximate seal segment groove flow area. The dimensions obtained during this inspection are shown schematically in Figures A-1 and A-2, and are tabulated in Table A1.

The depth (D) of the groove at any point was determined by taking the average thickness of the seal segment measured at the adjacent lands and subtracting the seal segment thickness at the groove.

$$D = \frac{A_{N-1} + A_N}{2} - C_N$$

where N is the number identifying adjacent seal grooves and lands.

FILLER STRIP AND TILE GAP MEASUREMENTS

The filler strip gaps and tile gap measurements were made by banding each row of seal segments around the core assembly.

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The filler strip gaps were measured one at a time by first, removing the insulating tile over the filler strip gap being measured. While still retaining the filler strips in position with the remainder of the tile, the filler strip gap between each row of banded seal rings was measured.

The gap measurements were made at 10 axial stations by means of flat thickness gages. Gaps greater than one mil could be measured within an estimated accuracy of ± 0.5 mils.

Gaps less than one mil were estimated with a hand honed 0.6 mil thickness gage. Generally where a filler strip gap existed, it existed over the entire radial length between the tile face surface and the core surface, although some radial tapering was noted at local stations.

A schematic showing the locations of the filler strip gap measurements are shown in Figures A-1 and A-3. Filler strip gap (F) measurements and tile gap (T) measurements are tabulated in Tables A2 and A3, respectively.

RADIAL STEPPING GAP

The radial stepping gap (G) of the filler strips was measured at each of the axial seal ring locations with thickness gages and the appropriate seal segments. During this measurement the core assembly was banded with the hose clamps around the seal segments. The radial stepping gap measurements were made during the assembly of the Build 1 Test 2 reflector-lateral support subassembly and for this particular model was found to be zero. A schematic showing the locations of the radial stepping gap measurements are shown in Figures A-1 and A-3.

The radial stepping gap (G) measurements of the tile are tabulated in Table A4.

CORE DIAMETER

Core diameter measurements were taken between each row of seal segments. Diameter measurements are tabulated in Table A5.

PLUNGER MEASUREMENTS

The plunger measurements (P) were made to (1) assure that the seal segments seated properly against the periphery of the core, and (2) determine a nominal cold preload bundling valve. Figure A-1 shows the dimensional locations of these measurements and the data are tabulated in Tables A6 and A7.

DIMENSIONAL CHANGES AND WEIGHT LOSS MEASUREMENTS

Dimensional changes and weight loss measurements were made where applicable in an attempt to estimate gross corrosion effects.

Since the surface regression pattern on the core surfaces existed over a large axial area and the corrosion depth varied across the flats, an axial line at mid-chord across each of the flats was arbitrarily selected as a common reference line for comparing the corrosion depth. These measurements were made utilizing a measuring and recording system specially designed to measure core surface regression by employing a Linear Variable Differential Transformer (LVDT).

Figures A-16 through A-18 shows the surface regression measured at mid-chord across the flats of the inner core.

The measured axial stations presented herein were accurate within $\pm 1/64$ of an inch. The corrosion depth was measured within an estimated accuracy of ± 1 mil.

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Pre and post test weight measurements of the filler strips, insulating tiles, simulated element core and seal segments are tabulated in Tables A8 and A10.

Dimensional changes on the surface of the filler strip were not able to be directly recorded on the measuring and recording system employed in measuring core regression. Local dimensional changes on the filler strips were measured with dial depth gage having a knife edge base and a push down point. The gage is operated by pressing down a push button on top so that the needle contacts the work surface to be measured. Depths up to 0.125 inch can be registered directly on the dial in 0.5 mils. Surface patterns including approximate envelopes of the corrosion, deposition, and plating areas with randomly selected corrosion measurements are illustrated in Figures A-18 through A-41. These illustrations are presented for general information to show the approximate relationship between related areas.

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Table A1
 HHT-7 Build 4 Test 1, Seal Segment Measurements

HHT 7 BUILD 4 TEST 1 SEAL SEGMENT MEASUREMENTS - INCHES																
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 1-SS1-T	.3740	.3631	.0109	.4420	.3745	.3621	.0121	.4435	.3740	.3625	.0117	.4413	.3740	.3628	.0112	.4420
R 1-SS1-B	.3739	.3620	.0119	.4411	.3740	.3620	.0120	.4426	.3738	.3620	.0119	.4415	.3740	.3631	.0108	.4418
R 1-SS2-T	.3742	.3640	.0102	.4416	.3743	.3640	.0102	.4421	.3745	.3625	.0119	.4414	.3742	.3627	.0116	.4430
R 1-SS2-B	.3738	.3625	.0113	.4413	.3738	.3631	.0107	.4452	.3745	.3625	.0116	.4415	.3750	.3630	.0117	.4418
R 1-SS3-T	.3742	.3629	.0113	.4418	.3741	.3630	.0111	.4428	.3741	.3625	.0116	.4442	.3741	.3625	.0116	.4417
R 1-SS3-B	.3742	.3623	.0119	.4411	.3745	.3631	.0112	.4431	.3742	.3625	.0118	.4418	.3745	.3625	.0118	.4419
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 2-SS1-T	.3735	.3625	.0110	.4424	.3734	.3630	.0104	.4426	.3735	.3625	.0109	.4421	.3735	.3628	.0107	.4440
R 2-SS1-B	.3741	.3625	.0116	.4418	.3741	.3632	.0109	.4420	.3740	.3628	.0112	.4412	.3738	.3629	.0110	.4418
R 2-SS2-T	.3748	.3650	.0098	.4420	.3745	.3632	.0114	.4421	.3746	.3635	.0111	.4432	.3746	.3635	.0111	.4424
R 2-SS2-B	.3748	.3640	.0108	.4421	.3750	.3633	.0116	.4422	.3752	.3631	.0120	.4414	.3750	.3635	.0116	.4420
R 2-SS3-T	.3741	.3620	.0121	.4421	.3745	.3629	.0114	.4429	.3745	.3625	.0120	.4420	.3745	.3630	.0115	.4421
R 2-SS3-B	.3732	.3615	.0117	.4416	.3740	.3624	.0112	.4420	.3740	.3624	.0116	.4416	.3746	.3628	.0115	.4421
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 3-SS1-T	.3740	.3625	.0115	.4429	.3740	.3625	.0115	.4427	.3740	.3630	.0110	.4434	.3742	.3628	.0113	.4419
R 3-SS1-B	.3739	.3620	.0119	.4419	.3740	.3625	.0115	.4418	.3740	.3629	.0111	.4415	.3741	.3630	.0110	.4418
R 3-SS2-T	.3740	.3640	.0100	.4417	.3740	.3635	.0105	.4425	.3735	.3629	.0108	.4413	.3739	.3618	.0119	.4419
R 3-SS2-B	.3739	.3645	.0094	.4412	.3740	.3640	.0099	.4422	.3740	.3635	.0105	.4415	.3741	.3628	.0112	.4420
R 3-SS3-T	.3745	.3640	.0105	.4421	.3745	.3631	.0114	.4422	.3745	.3630	.0115	.4421	.3747	.3630	.0116	.4427
R 3-SS3-B	.3745	.3637	.0108	.4414	.3747	.3635	.0111	.4418	.3742	.3626	.0118	.4415	.3745	.3630	.0113	.4418
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 4-SS1-T	.3740	.3635	.0105	.4419	.3742	.3623	.0113	.4434	.3745	.3630	.0107	.4425	.3745	.3635	.0110	.4425
R 4-SS1-B	.3739	.3621	.0118	.4416	.3740	.3625	.0115	.4428	.3740	.3625	.0115	.4415	.3740	.3635	.0105	.4418
R 4-SS2-T	.3749	.3645	.0104	.4420	.3748	.3635	.0113	.4424	.3750	.3635	.0114	.4419	.3740	.3632	.0116	.4420
R 4-SS2-B	.3752	.3640	.0112	.4412	.3750	.3638	.0113	.4424	.3748	.3630	.0119	.4412	.3749	.3625	.0123	.4420
R 4-SS3-T	.3746	.3635	.0111	.4422	.3745	.3630	.0115	.4426	.3742	.3630	.0113	.4417	.3745	.3628	.0116	.4420
R 4-SS3-B	.3740	.3630	.0110	.4416	.3740	.3630	.0110	.4412	.3745	.3628	.0115	.4414	.3745	.3630	.0115	.4416
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 5-SS1-T	.3740	.3625	.0115	.4417	.3740	.3625	.0115	.4419	.3740	.3625	.0115	.4425	.3740	.3619	.0121	.4409
R 5-SS1-B	.3735	.3620	.0115	.4412	.3740	.3625	.0112	.4418	.3740	.3625	.0115	.4412	.3741	.3625	.0115	.4413
R 5-SS2-T	.3750	.3650	.0100	.4423	.3750	.3636	.0114	.4434	.3745	.3630	.0117	.4422	.3729	.3625	.0112	.4431
R 5-SS2-B	.3748	.3633	.0115	.4419	.3749	.3630	.0118	.4415	.3746	.3627	.0120	.4415	.3731	.3630	.0119	.4423
R 5-SS3-T	.3750	.3630	.0120	.4425	.3755	.3636	.0116	.4425	.3752	.3635	.0118	.4414	.3748	.3632	.0118	.4419
R 5-SS3-B	.3746	.3625	.0121	.4418	.3750	.3630	.0118	.4419	.3748	.3635	.0114	.4415	.3740	.3625	.0119	.4413

Table A1 (Continued)

ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 6-SS1-T	.3732	.3652	.0080	.4439	.3732	.3638	.0094	.4440	.3732	.3635	.0097	.4422	.3732	.3645	.0037	.4424
R 6-SS1-B	.3732	.3645	.0087	.4439	.3730	.3641	.0090	.4439	.3730	.3640	.0090	.4426	.3728	.3645	.0034	.4425
R 6-SS2-T	.3745	.3655	.0090	.4445	.3745	.3662	.0033	.4442	.3745	.3662	.0083	.4432	.3745	.3650	.0095	.4420
R 6-SS2-B	.3745	.3658	.0087	.4445	.3745	.3662	.0083	.4442	.3745	.3652	.0093	.4433	.3745	.3652	.0093	.4426
R 6-SS3-T	.3735	.3655	.0080	.4445	.3735	.3645	.0090	.4441	.3735	.3635	.0100	.4427	.3735	.3640	.0095	.4424
R 6-SS3-B	.3730	.3645	.0085	.4444	.3728	.3645	.0034	.4440	.3728	.3635	.0093	.4424	.3733	.3645	.0045	.4427
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 7-SS1-T	.3745	.3661	.0084	.4433	.3742	.3650	.0094	.4441	.3745	.3641	.0102	.4433	.3743	.3645	.0099	.4432
R 7-SS1-B	.3745	.3652	.0093	.4446	.3745	.3652	.0093	.4441	.3750	.3652	.0095	.4424	.3745	.3655	.0093	.4429
R 7-SS2-T	.3749	.3655	.0094	.4450	.3745	.3658	.0089	.4449	.3743	.3665	.0079	.4439	.3750	.3651	.0095	.4422
R 7-SS2-B	.3745	.3649	.0096	.4450	.3743	.3656	.0090	.4427	.3746	.3660	.0087	.4441	.3750	.3652	.0096	.4430
R 7-SS3-T	.3735	.3650	.0085	.4439	.3733	.3635	.0099	.4450	.3735	.3637	.0097	.4421	.3730	.3645	.0087	.4422
R 7-SS3-B	.3735	.3645	.0090	.4442	.3735	.3640	.0095	.4442	.3735	.3642	.0093	.4425	.3731	.3648	.0045	.4423
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 8-SS1-T	.3740	.3655	.0085	.4437	.3735	.3638	.0099	.4424	.3735	.3650	.0085	.4433	.3735	.3642	.0093	.4423
R 8-SS1-B	.3735	.3650	.0085	.4437	.3732	.3645	.0088	.4435	.3732	.3641	.0091	.4431	.3732	.3649	.0043	.4424
R 8-SS2-T	.3741	.3661	.0080	.4439	.3741	.3661	.0080	.4442	.3745	.3670	.0073	.4439	.3745	.3652	.0093	.4434
R 8-SS2-B	.3742	.3651	.0091	.4442	.3745	.3660	.0083	.4440	.3748	.3650	.0096	.4435	.3747	.3661	.0086	.4424
R 8-SS3-T	.3735	.3661	.0074	.4435	.3735	.3650	.0085	.4439	.3731	.3638	.0095	.4425	.3730	.3638	.0093	.4427
R 8-SS3-B	.3732	.3648	.0084	.4437	.3732	.3647	.0085	.4440	.3731	.3642	.0089	.4422	.3728	.3639	.0090	.4421
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R 9-SS1-T	.3725	.3643	.0082	.4448	.3732	.3635	.0093	.4443	.3725	.3635	.0093	.4420	.3732	.3640	.0088	.4420
R 9-SS1-B	.3732	.3642	.0090	.4444	.3732	.3642	.0090	.4444	.3730	.3640	.0091	.4421	.3731	.3645	.0085	.4421
R 9-SS2-T	.3748	.3662	.0086	.4448	.3748	.3662	.0086	.4439	.3748	.3662	.0086	.4439	.3746	.3649	.0099	.4421
R 9-SS2-B	.3750	.3655	.0095	.4447	.3750	.3661	.0089	.4434	.3751	.3662	.0089	.4433	.3745	.3658	.0090	.4425
R 9-SS3-T	.3730	.3644	.0086	.4442	.3730	.3635	.0095	.4440	.3725	.3630	.0097	.4419	.3731	.3632	.0096	.4421
R 9-SS3-B	.3732	.3642	.0090	.4444	.3732	.3642	.0090	.4444	.3729	.3640	.0090	.4425	.3731	.3645	.0085	.4425
ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R10-SS1-T	.3745	.3665	.0080	.4445	.3745	.3660	.0085	.4440	.3732	.3650	.0089	.4425	.3720	.3632	.0094	.4430
R10-SS1-B	.3741	.3650	.0091	.4445	.3740	.3650	.0090	.4445	.3731	.3645	.0090	.4425	.3720	.3635	.0090	.4427
R10-SS2-T	.3745	.3652	.0093	.4443	.3740	.3646	.0096	.4440	.3735	.3665	.0072	.4432	.3725	.3640	.0090	.4428
R10-SS2-B	.3741	.3649	.0092	.4448	.3745	.3651	.0092	.4441	.3740	.3650	.0093	.4438	.3730	.3650	.0085	.4427
R10-SS3-T	.3740	.3660	.0080	.4434	.3740	.3645	.0095	.4440	.3731	.3640	.0095	.4425	.3740	.3645	.0090	.4427
R10-SS3-B	.3746	.3660	.0086	.4442	.3743	.3651	.0093	.4446	.3741	.3650	.0092	.4425	.3741	.3655	.0086	.4420

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Table A1 (Continued)

HHT 7 BUILD 4 TEST 1
SEAL SEGMENT MEASUREMENTS - INCHES

ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R11-SS1-T	.3745	.3675	.0070	.4438	.3750	.3670	.0077	.4435	.3745	.3670	.0077	.4445	.3750	.3675	.0072	.4435
R11-SS1-B	.3745	.3670	.0075	.4442	.3745	.3675	.0070	.4443	.3745	.3665	.0080	.4447	.3745	.3675	.0070	.4425
R11-SS2-T	.3740	.3670	.0070	.4446	.3745	.3670	.0072	.4452	.3745	.3665	.0080	.4445	.3745	.3670	.0075	.4440
R11-SS2-B	.3745	.3665	.0080	.4445	.3745	.3675	.0070	.4455	.3745	.3670	.0075	.4450	.3745	.3675	.0070	.4433
R11-SS3-T	.3745	.3685	.0060	.4442	.3745	.3665	.0080	.4441	.3745	.3675	.0070	.4441	.3750	.3675	.0072	.4442
R11-SS3-B	.3750	.3685	.0065	.4454	.3750	.3685	.0065	.4455	.3750	.3680	.0070	.4432	.3750	.3680	.0070	.4453

ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R12-SS1-T	.3745	.3675	.0070	.4450	.3745	.3675	.0070	.4435	.3745	.3675	.0070	.4439	.3740	.3670	.0072	.4436
R12-SS1-B	.3740	.3665	.0075	.4448	.3740	.3685	.0055	.4451	.3740	.3665	.0075	.4440	.3740	.3665	.0075	.4438
R12-SS2-T	.3740	.3670	.0070	.4446	.3740	.3670	.0070	.4444	.3745	.3670	.0072	.4451	.3745	.3675	.0070	.4443
R12-SS2-B	.3740	.3675	.0065	.4456	.3745	.3675	.0067	.4458	.3745	.3675	.0070	.4450	.3745	.3670	.0075	.4442
R12-SS3-T	.3745	.3675	.0070	.4464	.3750	.3680	.0067	.4445	.3750	.3680	.0070	.4444	.3750	.3680	.0070	.4440
R12-SS3-B	.3745	.3670	.0075	.4443	.3745	.3680	.0065	.4442	.3745	.3665	.0080	.4456	.3750	.3675	.0072	.4444

ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R13-SS1-T	.3735	.3660	.0075	.4447	.3735	.3660	.0075	.4442	.3735	.3660	.0075	.4440	.3735	.3660	.0075	.4442
R13-SS1-B	.3740	.3650	.0090	.4466	.3740	.3680	.0060	.4445	.3740	.3670	.0070	.4455	.3740	.3670	.0070	.4443
R13-SS2-T	.3735	.3675	.0060	.4448	.3735	.3665	.0070	.4451	.3735	.3660	.0075	.4448	.3735	.3670	.0065	.4444
R13-SS2-B	.3740	.3675	.0065	.4446	.3735	.3670	.0068	.4460	.3735	.3685	.0050	.4446	.3735	.3660	.0075	.4444
R13-SS3-T	.3745	.3675	.0070	.4437	.3740	.3660	.0082	.4443	.3740	.3675	.0065	.4442	.3740	.3670	.0070	.4437
R13-SS3-B	.3740	.3670	.0070	.4456	.3740	.3675	.0065	.4445	.3740	.3670	.0070	.4448	.3740	.3665	.0075	.4435

ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R14-SS1-T	.3740	.3665	.0075	.4442	.3740	.3660	.0080	.4444	.3740	.3665	.0075	.4424	.3740	.3665	.0075	.4440
R14-SS1-B	.3730	.3665	.0065	.4454	.3735	.3660	.0072	.4455	.3730	.3660	.0072	.4452	.3740	.3665	.0070	.4430
R14-SS2-T	.3735	.3670	.0065	.4442	.3735	.3665	.0070	.4443	.3730	.3665	.0067	.4442	.3730	.3665	.0065	.4440
R14-SS2-B	.3730	.3665	.0065	.4457	.3735	.3670	.0063	.4459	.3735	.3660	.0075	.4458	.3730	.3660	.0072	.4440
R14-SS3-T	.3745	.3675	.0070	.4445	.3745	.3675	.0070	.4444	.3745	.3675	.0070	.4443	.3745	.3665	.0080	.4436
R14-SS3-B	.3745	.3675	.0070	.4452	.3745	.3675	.0070	.4448	.3745	.3670	.0075	.4438	.3745	.3670	.0075	.4439

ID. NO.	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R15-SS1-T	.3740	.3680	.0060	.4441	.3745	.3660	.0082	.4444	.3740	.3670	.0072	.4440	.3740	.3665	.0075	.4433
R15-SS1-B	.3745	.3680	.0065	.4454	.3745	.3675	.0070	.4441	.3740	.3675	.0067	.4434	.3740	.3665	.0075	.4438
R15-SS2-T	.3735	.3660	.0075	.4441	.3735	.3665	.0070	.4438	.3725	.3665	.0065	.4435	.3730	.3665	.0062	.4417
R15-SS2-B	.3735	.3660	.0075	.4459	.3735	.3660	.0075	.4448	.3735	.3665	.0070	.4446	.3735	.3665	.0070	.4440
R15-SS3-T	.3745	.3670	.0075	.4436	.3740	.3670	.0072	.4450	.3745	.3665	.0077	.4435	.3740	.3665	.0077	.4436
R15-SS3-B	.3740	.3670	.0070	.4442	.3740	.3670	.0070	.4448	.3745	.3665	.0077	.4431	.3740	.3665	.0077	.4446

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Table A1 (Continued)

ID. NO.	HHT 7 BUILD 4 TEST 1															
	SEAL	SEGMENT	MEASUREMENTS				- INCHES									
	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	F4
R16-SS1-T	.3727	.3652	.0075	.4445	.3733	.3664	.0066	.4451	.3740	.3664	.0072	.4447	.3740	.3658	.0082	.4445
R16-SS1-B	.3738	.3660	.0078	.4451	.3740	.3658	.0081	.4450	.3740	.3655	.0085	.4448	.3740	.3660	.0080	.4448
R16-SS2-T	.3735	.3648	.0087	.4454	.3735	.3663	.0072	.4451	.3737	.3660	.0076	.4444	.3735	.3661	.0075	.4449
R16-SS2-B	.3734	.3652	.0082	.4451	.3735	.3652	.0082	.4438	.3735	.3650	.0085	.4449	.3737	.3660	.0076	.4444
R16-SS3-T	.3730	.3649	.0081	.4444	.3728	.3660	.0069	.4438	.3728	.3661	.0067	.4448	.3728	.3652	.0076	.4442
R16-SS3-B	.3721	.3649	.0072	.4455	.3726	.3648	.0076	.4432	.3723	.3642	.0082	.4452	.3726	.3649	.0075	.4450
	A1	C1	D1	E1	A2	C2	D2	E2	A3	C3	D3	E3	A4	C4	D4	E4
R17-SS1-T	.3745	.3675	.0070	.4440	.3745	.3665	.0080	.4437	.3740	.3675	.0067	.4435	.3745	.3680	.0062	.4433
R17-SS1-B	.3745	.3670	.0075	.4455	.3745	.3675	.0070	.4444	.3745	.3675	.0070	.4436	.3745	.3670	.0075	.4436
R17-SS2-T	.3730	.3670	.0060	.4452	.3720	.3650	.0075	.4444	.3710	.3640	.0075	.4441	.3700	.3640	.0065	.4440
R17-SS2-B	.3730	.3665	.0065	.4438	.3720	.3650	.0075	.4451	.3710	.3640	.0075	.4447	.3700	.3635	.0070	.4438
R17-SS3-T	.3740	.3665	.0075	.4442	.3740	.3665	.0075	.4436	.3740	.3665	.0075	.4440	.3740	.3665	.0075	.4441
R17-SS3-B	.3740	.3665	.0075	.4458	.3745	.3680	.0062	.4453	.3745	.3675	.0070	.4435	.3740	.3670	.0072	.4438

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Table A2
Filler Gap Measurements - HHT-7 Build 4 Test 1

Axial Station (Inches)	F - Filler Gap Measurements - Mils											
	F(1-2)	F(2-3)	F(3-4)	F(4-5)	F(5-6)	F(6-7)	F(7-8)	F(8-9)	F(9-10)	F(10-11)	F(11-12)	F(12-1)
1	1.0	.6	1.0	.6	1.0	.6-	.6-	.6-	.6	.6+	.6-	.6
5	.6	.6	1.0	.6-	1.0	.6	.6-	.6-	.6	.6+	.6-	.6-
10	.6	.6-	1.0	.6-	2.0	.6	.6-	.6	.6	.6	.6	.6+
15	.6+	.6	.6+	.6	1.5	.6	.6	.6	.6	.6	.6	.6
20	.6+	.6	.6	.6	1.5	.6-	.6	.6	.6	.6-	.6	.6
25	.6+	.6	.6	.6	.6	.6	.6	.6	.6	.6-	.6	.6
30	.6	.6-	.6+	.6	.6	.6	.6-	.6-	.6	.6	.6	.6
35	.6+	1.0	1.0	.6	.8	.6	.6-	.6	.6	.6	.6-	.6
40	.6	1.0	1.5	1.0	1.5	.6-	.6-	.6-	.6	.6	.6-	.6
45	.6+	2.0	1.5	1.0	.6	.6	.6-	.6-	.6	.6	.6-	.6

NOTE: 0.6+ indicates a gap greater than 0.6 but less than 1.
0.6- indicates a gap less than 0.6 but greater than 0.

Table A3
Insulating Tile Gap Measurements - HHT-7 Build 4 Test 1

Axial Station (Inches)	T - Tile Gap Measurements - Mils											
	T(1-2)	T(2-3)	T(3-4)	T(4-5)	T(5-6)	T(6-7)	T(7-8)	T(8-9)	T(9-10)	T(10-11)	T(11-12)	T(12-1)
1	1.5	1.5	1.0	1.0	2.0	1.5	.6+	.6+	.6	.6	.6	.6
5	.6	.6-	.6	1.0	.6	3.0	1.5	.6	.6	.6+	.6	.6
10	.6	.6-	.6	.6+	1.0	3.0	4.0	.6	.6	1.0	.6-	.6
15	.6	.6-	1.0	.6+	.6	3.0	3.5	.6	.6	.6	.6	.6+
20	.6	.6	.6	.6	2.0	2.5	2.0	.6	.6	.6	.6	.6
25	.6	.6-	.6-	.6			1.5	.6-	.6	.6	.6	.6
30	.6	.6-	.6	.6-	3.0	1.0	.6	.6-	1.0	.6	.6+	1.0
35	.6	.6	.6	.6-	3.0	1.0	.6-	.6-	1.0	.6	.6+	.6
40	.6+	.6	.6	.6	2.0	1.0	.6	.6	1.0	.6	1.0	.6+
45	2.0	1.0	1.0	1.5	2.0	.6+	.6	1.0	.6	1.0	1.0	1.0

NOTE: 0.6+ indicates a gap greater than 0.6 but less than 1.

0.6- indicates a gap less than 0.6 but greater than 0.

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Table A4

Stepping Gap Measurements - HHT-7 Build 4 Test 1

Axial Station (Inches)	Seal Row Number	G - Stepping Gap Measurements - Mils											
		T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12
		<u>Seal Inlet</u>											
.25	1	.6	.6	.6	.6+	.6	1.0	.6	.6	.6	.6	.6+	1.0
2.81	2							.6	.5	.6		.6+	.6
5.63	3												
8.44	4											.6	
11.25	5												
14.07	6		.6										
16.88	7						1.5						
19.69	8								1.5				
22.50	9							.6					
25.32	10					.6							1.0
28.13	11			1.0									
30.94	12		.6			.6							1.5
33.76	13	.6		.6	.6						.6	.6	.6+
36.57	14												
42.20	16		.6		.6						.6	.6	1.0
45.01	17							.6	1.0		1.0	.6	.6

Seal Outlet

1.75	1		.6			.6	.6	.6	.6	.6			
4.32	2						.6	.6					
7.13	3		.6	1.0	.6+								
9.94	4				1.5								
12.75	5												
15.57	6												
18.38	7												

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Table A4 (Continued)

Axial Station (Inches)	Seal Row Number	G - Stepping Gap Measurements - Mils											
		T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12
<u>Seal Outlet (Continued)</u>													
21.19	8											2	
24.00	9			.6									
26.82	10			1.0						.6			
29.63	11					.6					.6	.6	
32.44	12	.6					.6+						
35.26	13			.6	.6								
38.07	14							.6					
43.70	16							.6					
46.51	17	1.0										.6	

NOTE: Values zero except where otherwise noted.

0.6+ indicates a gap greater than 0.6 but less than 1.

0.6- indicates a gap less than 0.6 but greater than 0.

Table A5

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Core Diameter Measurements - HHT-7 Build 4 Test 1

Axial Station (Inches)	D - Diameter Measurements - Inches					
	D(1-7)	D(2-8)	D(3-9)	D(4-10)	D(5-11)	D(6-12)
2.28	3.504	3.504	3.502	3.503	3.5035	3.502
4.98	3.503	3.502	3.5005	3.5015	3.503	3.5035
7.79	3.504	3.503	3.501	3.503	3.501	3.5035
10.70	3.505	3.504	3.503	3.503	3.5065	3.504
13.41	3.504	3.506	3.503	3.503	3.504	3.5025
16.23	3.502	3.503	3.503	3.5035	3.5035	3.503
19.04	3.503	3.502	3.502	3.5035	3.503	3.504
21.85	3.501	3.503	3.506	3.5015	3.5025	3.5015
24.66	3.501	3.502	3.5025	3.501	3.503	3.501
27.48	3.500	3.502	3.502	3.5015	3.5025	3.504
30.29	3.501	3.504	3.502	3.502	3.5025	3.501
33.10	3.503	3.503	3.502	3.503	3.5035	3.502
35.92	3.503	3.503	3.503	3.5025	3.5025	3.5025
38.73	3.5035	3.503	3.5025	3.503	3.503	3.502
41.54	3.5035	3.5005	3.5025	3.502	3.502	3.5035
43.73	3.503	3.5025	3.502	3.502	3.5025	3.501

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Table A6
Reflector to Plunger Measurement - Inches

Location	Plunger Number					
	1	2	3	4	5	6
R 1-P-	.472	.475	.461	.438	.457	.470
R 2-P-	.476	.471	.452	.445	.450	.468
R 3-P-	.482	.473	.457	.446	.465	.473
R 4-P-	.482	.475	.455	.450	.455	.472
R 5-P-	.470	.455	.428	.437	.440	.455
R 6-P-	.478	.474	.454	.446	.459	.470
R 7-P-	.477	.461	.447	.435	.446	.460
R 8-P-	.472	.470	.458	.450	.450	.462
R 9-P-	.470	.476	.454	.447	.453	.463
R10-P-	.464	.467	.460	.445	.446	.457
R11-P-	.469	.464	.459	.474	.450	.453
R12-P-	.460	.432	.447	.443	.445	.448
R13-P-	.467	.463	.469	.460	.452	.445
R14-P-	.470	.464	.472	.455	.456	.439
R15-P-	.448	.470	.469	.463	.443	.435
R16-P-	.439	.466	.463	.460	.433	.421
R17-P-	.421	.456	.477	.470	.434	.430

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Table A7

Total Spacer Thickness for Plunger Spring Assembly

Location	Spacer Thickness Used - Inches					
	1	2	3	4	5	6
R 1-P-	.102	.103	.084	.066	.085	.099
R 2-P-	.101	.099	.079	.070	.078	.096
R 3-P-	.105	.099	.079	.070	.083	.098
R 4-P-	.105	.104	.078	.070	.083	.098
R 5-P-	.095	.083	.054	.068	.068	.082
R 6-P-	.105	.103	.060	.070	.086	.099
R 7-P-	.100	.099	.079	.062	.069	.090
R 8-P-	.099	.099	.079	.075	.075	.082
R 9-P-	.081	.094	.090	.070	.092	.090
R10-P-	.087	.095	.079	.070	.073	.097
R11-P-	.093	.085	.079	.093	.082	.089
R12-P-	.078	.060	.072	.071	.072	.073
R13-P-	.104	.102	.102	.082	.082	.072
R14-P-	.096	.096	.102	.082	.085	.068
R15-P-	.071	.098	.097	.092	.070	.063
R16-P-	.059	.068	.065	.068	.064	.056
R17-P-	.048	.080	.106	.072	.068	.057

Table A8

Simulated Element and Filler Strip Weight Measurements
HHT-7 Build 4 Test 1

Identification Number		Weight - Grams		
		Pre Weight	Post Weight	Weight Loss
Element	S/N 5	2680.8	1 2906.9	
F-1	S/N 5	710.2	707.0	2 3.2
F-2	S/N 5	324.1	323.6	2 .5
F-3	S/N 5	711.2	707.0	2 4.2
F-4	S/N 5	331.1	329.8	2 1.3
F-5	S/N 5	709.9	705.8	2 4.1
F-6	S/N 5	330.0	328.0	2 2.0
F-7	S/N 5	722.7	710.7	3 12.0
F-8	S/N 5	328.0	325.7	2.3
F-9	S/N 5	710.7	706.7	4.0
F-10	S/N 5	330.5	329.4	1.1
F-11	S/N 5	713.1	708.8	4.3
F-12	S/N 5	327.9	326.2	1.7

- 1 Includes added boron nitride insulator and loss of C-14 cement in inside wall.
- 2 Includes coating weight loss.
- 3 Not representative, includes loss of pin, reference post test photograph, Figure 21A

Table A9

Tile Weights
HHT-7 Build 4 Test 1

Identification Number	Weight - Grams		
	Pre Weight	Post Weight	Weight Loss
T-1 S/N	244.1	242.7	1.4
T-2 S/N	244.0	242.8	1.2
T-3 S/N	244.1	243.0	1.1
T-4 S/N	243.9	242.8	1.1
T-5 S/N	244.3	243.2	1.1
T-6 S/N	239.4	238.3	1.1
T-7 S/N	239.1	238.0	1.1
T-8 S/N	244.0	242.9	1.1
T-9 S/N	244.2	242.95	2.005
T-10 S/N	244.8	242.5	2.3
T-11 S/N	244.0	243.4	.6
T-12 S/N	244.0	243.8	.2

Table A10

Seal Segment Weight Measurements
HHT-7 Build 4 Test 1

Identification Number	Weight - Grams			Type of Graphite
	Pre Test	Post Test	Weight Loss
R1-1	56.2	56.1	.1	ATJ
R1-2	56.2	56.0	.2	ATJ
R1-3	58.0	57.8	.2	ATJ
R2-1	58.6	58.5	.1	ATJ
R2-2	59.0	59.0	0	ATJ
R2-3	58.5	58.4	.1	ATJ
R3-1	58.1	58.1	0	ATJ
R3-2	56.1	56.1	0	ATJ
R3-3	59.6	59.4	.2	ATJ
R4-1	60.3	60.3	0	ATJ
R4-2	57.1	57.0	.1	ATJ
R4-3	59.4	59.3	.1	ATJ
R5-1	60.5	60.5	0	ATJ
R5-2	62.3	62.3	0	ZTA
R5-3	56.9	56.6	.3	ATJ
R6-1	58.1	58.0	.1	ATJ
R6-2	57.8	57.6	.2	ATJ
R6-3	61.2	61.2	0	ATJ
R7-1	59.0	58.8	.2	ATJ
R7-2	56.2	56.2	0	ATJ
R7-3	58.9	58.8	.1	ATJ
R8-1	58.9	58.7	.2	ATJ

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Table A10 (Continued)

Identification Number	Weight - Grams			Type of Graphite
	Pre Test	Post Test	Weight Loss
R8-2	60.1	60.1	0	ATJ
R8-3	59.1	59.0	.1	ATJ
R9-1	60.6	60.5	.1	ATJ
R9-2	58.0	57.9	.1	ATJ
R9-3	59.8	59.6	.2	ATJ
R10-1	65.3	65.3	0	ZTA
R10-1	64.5	64.5	0	ZTA
R10-3	67.1	67.1	0	ZTA
R11-1	60.5	60.5	0	ATJ
R11-2	58.2	58.3	+.1	ATJ
R11-3	59.7	59.6	.1	ATJ
R12-1	60.0	59.9	.1	ATJ
R12-2	58.9	58.9	0	ATJ
R12-3	59.1	59.0	.1	ATJ
R13-1	59.2	59.1	.1	ATJ
R13-2	58.4	58.4	0	ATJ
R13-3	61.0	60.9	.1	ATJ
R14-1	59.2	59.2	0	ATJ
R14-2	56.9	56.7	.2	ATJ
R14-3	60.9	60.8	.1	ATJ
R15-1	58.3	58.3	0	ATJ
R15-2	58.9	58.7	.2	ATJ
R15-3	58.5	58.4	.1	ATJ
R16-1	52.1	51.7	.4	ATJ
R16-2	55.8	55.5	.3	ATJ

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A10 (Continued)

Identification Number	Weight - Grams			Type of Graphite
	Pre Test	Post Test	Weight Loss
R16-3	56.1	55.2	.9	ATJ
R17-1	60.5	60.5	0	ATJ
R17-2	58.6	58.5	.1	ATJ
R17-3	59.1	59.0	.1	ATJ

Measured weight loss due to small locally chipping inherent in a post test disassembly.

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VIEW LOOKING DOWNSTREAM

611102-28

Figure A-1

Model Component Measurement Schematic

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Figure A-2

Seal Segment Measurement Schematic

611102-4B

Figure A-3
Filler Strip Measurement Schematic

Figure A-4

HHT-7 Build 4 Test 1, Hot Buffer General Assembly

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- 16 A MAXIMUM OF .010 TWIST IS PERMISSIBLE OVER THE ENTIRE LENGTH OF ANY LONGITUDINAL FACE IN THE RESTRAINED FLATTENED POSITION
- 17 THE ALLOWABLE BOW ALONG SURFACE [E] SHALL BE .002 IN THE RESTRAINED FLATTENED POSITION
- 18 NO MORE THAN .060 OF THE AS DEPOSITED MATERIAL SHALL BE REMOVED FROM THE SUBSTRATE SURFACE
- 19 SECTION 4.4.1 OF PDS 30016.3 IS NOT APPLICABLE
- 20 MICROSTRUCTURE SHALL BE ONLY SLIGHTLY RENUCLEATED PER P294601.1 FIGURE 4 AS MAXIMUM CONDITION RANGING TO FIGURE 7
- 21 THE SYMBOL INDICATES CONTOUR TOTAL TOLERANCE AND IS USED WHERE A UNIFORM AMOUNT OF VARIATION IS PERMITTED ALONG A CONTOUR
- 22 ACTUAL EXTERIOR SURFACES IN ANY PLANE CUT PERPENDICULAR TO THE .46 .075 DIMENSION TO BE WITHIN TOLERANCE ENVELOPE SHOWN
- 23 BASAL PLANE ORIENTATION TO BE PERPENDICULAR TO CENTER PLANE [G] WITHIN 1° 30'
- 24 A NODULE WHOSE MAJOR DIAMETER ON ONE SURFACE MINUS THE MAJOR DIAMETER ON THE OPPOSITE SURFACE IN EXCESS OF THE WALL THICKNESS IS SUBJECT TO REJECTION
- 25 WATER OR OTHER MACHINING LUBRICANTS NOT PERMITTED
- 26 NO DELAMINATIONS PERMITTED ON FINISH MACHINED SURFACES AS DETERMINED BY VISUAL INSPECTION AT 2½ MAGNIFICATION
- 27 THE ALLOWABLE BOW ALONG SURFACE [F] SHALL BE .150 MAXIMUM FREE STANDING
- 28 BREAK SHARP EDGES .005 MAXIMUM EXCEPT THOSE DEFINED BY TOLERANCE ENVELOPE OR OTHERWISE SPECIFIED
- 29 TAG IDENT NT 101487 ITEM NO
- 30 DIMENSIONS BASED ON 68° F
- 31 INTERPRET THIS DRAWING PER MIL D 70327 EXCEPT NOTE 11

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Figure A-6

HHT-7 Build 4 Test 1, Hot Buffer Filler Strips

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Figure A-7

HHT-7 Build 4 Test 1, Furnace Components

~~_____~~

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THIS VIEW SHOWS THE DETAIL OF THE
FLOW SLOTS IN ITEMS 501 THRU 512

ITEM NR	DIM 'Y
501, 502, 503	007
504, 505, 506	008
507, 508, 509	009
510, 511, 512	011
513, 514, 515	050

SCALE 1/1

VIEW A-A

VIEW B B

VIEW D D
TYP FOR ITEMS 501 504 507
510, 502 505, 508, 511, 515 & 516

VIEW C-C

SCALE 1/1

- ▶ BUY FROM HIGH TEMP MATERIALS, LOWELL, MASS , OR EQUAL.
- ▶ BUY FROM NATIONAL CARBON CO. NEW YORK, IT, N.Y. OR EQUAL.
- ▶ ROUGH MACHINED BLANK & FINISHED PART TO BE INSPECTED PER PP2494-1 SEPARATION DISTANCE BETWEEN ANY TWO VOIDS, CRACKS, INCLUSIONS OR OTHER DEFECTS DETECTABLE AT 2% SENSITIVITY SHALL BE 2.00 MINIMUM MAXIMUM DEFECT SIZE SHALL BE .032
- ▶ TAG IDENT AS FOLLOWS
HT701628-1178M.N3.

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SECTION D-D

SECTION E-E

Figure A-13

HHT-7 Build 4 Test 1, Model Components

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Figure A-14

HHT-7 Build 4 Test 1, Model Components

- 4 AGSR OR GRAPHITE G
- 3 TAG IDENT NT 701509 - ITEM NO
- 2- UNLESS OTHERWISE SPECIFIED
 - A DIMENSIONS BASED ON 68°F
 - B REMOVE ALL BURRS & BREAK ALL SHARP EDGES .005 TO .015 RADIUS OR CHAMFER
 - C-INTERNAL CORNERS SHALL HAVE FILLETS OF .015 R MAX
- 1- INTERPRET THIS DWG PER MIL D 70327

Figure A-15
 HHT-7 Build 4 Test 1, Heater Rod

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Figure A-16

Mid-Chord Inner Core Surface Regression Profile

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Figure A-17

Mid-Chord Inner Core Surface Regression Profile

Figure A-18
 Sketches of Corrosion Patterns on Filler Strip Surfaces, F-1

Figure A-19
 Sketches of Corrosion Patterns on Filler Strip Surfaces, F-2

Figure A-20

Sketches of Corrosion Patterns on Filler Strip Surfaces, F-3

Figure A-21

Sketches of Corrosion Patterns on Filler Strip Surfaces, F-4

Figure A-22
 Sketches of Corrosion Patterns on Filler Strip Surfaces, F-5

Figure A-23

Sketches of Corrosion Patterns on Filler Strip Surfaces, F-6

Figure A-24

Sketches of Corrosion Patterns on Filler Strip Surfaces, F-7

Figure A-25
Sketches of Corrosion Patterns on Filler Strip Surfaces, F-8

Figure A-26

Sketches of Corrosion Patterns on Filler Strip Surfaces, F-9

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A: [REDACTED]

Figure A-27

Sketches of Corrosion Patterns on Filler Strip Surfaces, F-10

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Figure A-28

Sketches of Corrosion Patterns on Filler Strip Surfaces, F-11

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Figure A-29
Sketches of Corrosion Patterns on Filler Strip Surfaces, F-12

Figure A-30
Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-1

Figure A-31

Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-2

Figure A-32

Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-3

Figure A-33

Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-4

Figure A-34

Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-5

Figure A-35
 Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-6

Figure A-36
Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-7

Figure A-37

Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-8

Figure A-38

Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-9

Figure A-39
Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-10

Figure A-40
 Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-11

Figure A-41

Sketches of Corrosion Pattern on Insulating Tile Surfaces, T-12

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APPENDIX B PRELIMINARY FUNCTIONAL CHECKOUT TESTS

Since the hot hydrogen flow tests is essentially a "one shot" type test, it is less risky to establish operating test conditions by first conducting preliminary functional checkout tests with fluids that do not react with graphite. Preliminary functional checkout tests with hydrogen at ambient temperature and with helium at intermediate power levels were conducted to determine the flow-temperature-pressure characteristics of the model.

A description of these tests follows.

HHT-7-4-1-CH2-3

The first of the two checkout tests was conducted with ambient temperature gas at hydrogen flow rates ranging from 0.011 lb/sec to 0.026 lb/sec. Pressure drop varies from 5 psi to 53 psi with a constant model back pressure maintained at approximately 545 psig. Pressure and flow rate data are presented in Figures B-1 and B-2.

Figure B-1 shows the flow rate measured through each of the parallel flow systems; i. e., core proper flow, total helium flow, heater atmosphere supply, internal leakage, and No. 5 view port coolant flow as a function of model pressure drop. Total helium flow includes heater atmosphere leakage and internal leakage. Internal leakage includes seal and chuck leakage and porous reflector flow.

Figure B-2 shows a straight line plot of the normalized axial pressure distribution determined by the core inlet and exit pressures and two axial seal cavity pressures.

HHT-7-4-1-HHE-3

The second test conducted utilized hot helium gas through the core proper.

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Helium flow rates were varied from 0.009 lb/sec to 0.024 lb/sec with constant model back pressure maintained at about 545 psig. Pressure drop across the model varied from 10 to 78 psi with maximum core temperatures at each power set point varying from 290°F to 2880°F

Figure B-3 shows the flow rate measured through each of the parallel flow systems as it varied with model pressure drop.

Figure B-4 shows the normalized axial pressure distribution.

Figure B-5 shows the estimated temperature power level characteristics for core station 34.15 inches based on extrapolated hot helium test data and the approximate power level required to satisfy operating temperature conditions.

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- PRIMARY HYDROGEN FLOW
- TOTAL HELIUM ATMOSPHERE FLOW
- △ HEATER HELIUM ATMOSPHERE FLOW
- ◇ VIEW PORT NUMBER 5 COOLANT FLOW
- INTERNAL ATMOSPHERE LEAKAGE FLOW

Figure B-1

Model Flow Characteristics From Cold Hydrogen Flow Test
Test Number HHT-7-4-1-CH2-3

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$P_2 = 560$ PSIA = CONSTANT

$P_x = 41.8$ INCHES, OMITTED
 BECAUSE OF LEAK IN
 SENSOR PROBE

$\dot{m}_1 =$ HYDROGEN FLOW RATE
 THROUGH PRIMARY
 FLOW SYSTEM

Figure B-2

Normalized Pressure Ratio Distribution
 Test Number HHT-7-4-1-CH2-3

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- HELIUM FLOW THROUGH HYDROGEN SYSTEM
- TOTAL HELIUM ATMOSPHERE FLOW
- △ HEATER HELIUM ATMOSPHERE FLOW
- ◇ VIEW PORT NUMBER 5 COOLANT FLOW
- INTERNAL ATMOSPHERE LEAKAGE FLOW

Figure B-3

Model Flow Characteristics From Hot Helium Flow Test
Test Number HHT-7-4-1-HHE-3

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Figure B-4

Normalized Pressure Ratio Distribution
Test Number HHT-7-4-1-HHE-3

Figure B-5

Estimated Model Power-Temperature Characteristics for
Core Station 34.15 Inches Based on Extrapolated Hot Helium Test Data
Test Number HHT-7-4-1-HHE-3

APPENDIX C
PRELIMINARY ZrC COATING INFORMATION

A discussion follows which

1. relates the history of the ZrC coating filler strips utilized in the Build 4 Test 1 model, and
2. describes an isothermal narrow slot test which was conducted to supply preliminary support information for the model test.

Six filler strips were initially coated by the Ceramic Fuel Laboratory on August 27, 1965. The ZrC coating was applied by a technique proposed to coat NRX-A core parts. The Zr powder was applied as a paint and the part was then rapidly heated to a temperature at which the Zr would flow and carbide with the graphite. Visual inspection of the coated filler strips showed that the ZrC coating had bubbled in certain areas in two (2) of the filler strips. The reason for this bubbling effect was explained as a lack of experience in the use of the spray gun.

Following the first phase coating operation, the filler strips were delivered to the Experimental Fuel Laboratory for high temperature carbiding process. When taken from the furnace, the coating showed effects of blistering. This effect was attributed to contaminated helium gas, which was used as an inert atmosphere during the carbiding process. Figures C-1A and C-2A show the effects of this blistering. A second coating operation followed after first removing the coating mechanically from the filler strips. The carbiding process which followed the first stage coating application during the first trial operation was not utilized in the second coating process. Figures C-1B and C-2B show the surface condition of this coating at the hot end section of the filler strip. Figures C-1C and C-2C show the post test condition of the coating. Note that the area around the key is poorly coated which showed up unfavorably under test. Also of interest are conditions of the coatings applied to filler strip F-3 and F-5. Note that the heaviest corrosion attack occurred where the coating appeared to be rough.

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Figures C-3 through C-6 show a comparison of the pre and post test condition along the full length of the filler strip. The test results show that where the coating appeared to be relatively good and adhered properly to the filler strips; the filler strip surface was satisfactorily protected. This conclusion also was tentatively verified from the results obtained from an isothermal narrow slot test utilizing the HHT-6 test apparatus^(a). Related information from the results of this test is also present herein.

The test section employed in the HHT-6 test apparatus is an axially split graphite cylinder containing a gap that is varied in thickness from 0.001 inch to 0.006 inch, the width of the slot is 1 inch, its length 2 inches. All the support hardware is fabricated of molybdenum to eliminate the generation of extraneous hydrocarbons.

Two sets of flow slots were coated with NbC on one face and ZrC on the other face. All these fixtures were tested at 3500°R for 30 minutes with hydrogen flows approaching 0.0001 lb/sec at 200 psig inlet pressure. Data to date shows that the temperature gradient along the axis of the test fixture is approximately 25 degrees, the exit end being the hotter. Material temperature levels from test to test can vary as much as 140 degrees as a maximum.

Figure C-7 shows the ZrC coated surfaces of fixtures 3 and 4. The appearance of the two coated parts are quite different even though the two parts were coated by the same process. The coating on piece Serial Number 3 appears to be shiny, smooth and impervious. The coating on piece Serial Number 4 appears to be dull, rough and porous.

Serial Number 3 specimen was run in helium for 30 minutes. Figure C-8 shows the surfaces of the fixture before test.

(a) WANL-TME-1430

WANL-TME-1462

Figure C-9 shows the condition of the coated surfaces after the run. The NbC coating shows less discoloration than the ZrC coating, microscopic examination of both inlet edges revealed small cracks and local areas of spalling. This fixture was then tested at 3500°R in hydrogen for 30 minutes.

Figure C-10 shows the surfaces of the flow slot after test. The NbC coating is totally intact except for some local removal at the inlet edge. The ZrC coating also appears totally intact except for removal along the inlet and outlet edge. Serial Number 4 having the NbC-ZrC coating combination was next to be tested. This specimen was run at 3500°R in hydrogen for 30 minutes. No helium run was performed as was on Serial Number 3. Figure C-11 shows the coated surfaces of the flow groove prior to test. Cross hatch pattern clearly visible on the NbC coating is the reference used while the measurement data is being taken.

Figure C-12 is a photograph of the coated surfaces of the flow slot. The NbC coating is totally intact while no trace of the ZrC coating exists.

The information obtained from the NbC-ZrC coated flow slots indicates that the coating is effective in protecting the graphite from hydrogen corrosion. The results imply that a problem exists in some phase of the coating technique as demonstrated by the different characteristics displayed by two test fixtures coated by the same method.

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Figure C-1

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C-2a: RESULTS OF FIRST COATING ATTEMPT

C-2b: PRETEST CONDITION OF COATING

NOTE: PRE AND POST TEST, COATING CONDITION.

C-2c: POST TEST CONDITION OF COATING

Figure C-2

Photographs Showing Comparative Coating Conditions

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Figure C-3
Comparison Photographs Showing
Pre and Post Test Conditions of Coated Filler Strips

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C-4a: PRE TEST COATING CONDITION

C-4b: POST TEST COATING CONDITION

Figure C-4

Comparison Photographs Showing
Pre and Post Test Conditions of Coated Filler Strips

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C-5a: PRE TEST COATING CONDITION

C-5b: POST TEST COATING CONDITION

Figure C-5

Comparison Photographs Showing
Pre and Post Test Conditions of Coated Filler Strips

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C-6a: PRE TEST COATING CONDITION

C-6b: POST TEST COATING CONDITION

Figure C-6
Comparison Photographs Showing
Pre and Post Test Conditions of Coated Filler Strips

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Figure C-7

Photographs Showing Comparison of Coating Condition

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Figure C-8

Pre Test Photograph of Test Specimen Number 3

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Figure C-9

Post Test Photograph of Test Specimen Number 3
After Hot Helium Flow Test

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Figure C-10

Post Test Photograph of Test Specimen
After Hot Hydrogen Flow Test

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Figure C-11
Pre Test Photograph of Test Specimen Number 4

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Figure C-12

Post Test Condition of Test Specimen Number 4
After Hot Hydrogen Flow Test

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C15

APPENDIX D HEATER ELEMENT DESIGN DETAILS

In order to obtain temperature profiles in the HHT-7 Filler Strip Test Model, which are compatible with the current reactor temperature distributions, a tapered graphite radiation heater was designed and tested prior to the model test. To achieve the desired temperature level in the model, extremely high material temperatures have to be realized (circa 6000°R) along with high heat fluxes on the heater surface. The heaters were run in a stagnant helium atmosphere in order to increase heater performance.

Appendix D describes the method used in designing the tapered graphite rod heater for the HHT-7 Build 4 Test 1 model. Included in this section is pertinent test results from Build 4 Test 1 and the limited results realized while testing the heater in the A-10 furnace using only the current conducting parts of the test model.

The results of this investigation indicate that a heater can be designed to yield the desired temperature distributions, but the life of the heaters due to the high temperature levels and heat flux is not compatible with long term testing.

FORMULATION OF EQUATIONS

An example of a typical design temperature distribution required on the hot and cold side of the pyrotile is shown in Figure D1. The radial heat conduction equation with no heat generation is

$$q = \frac{(T_{PH} - T_{PC}) 2\pi k L}{\ln r_{PC}/r_{PH}} \quad (1)$$

See Figure D2 for nomenclature. The area of the pyro cool side is:

$$A_{PC} = \pi D_{PC} L$$

and

$$q''_{PC} = \frac{(T_{PH} - T_{PC}) 2 k(t)}{D_{PG} \ln r_{PC}/r_{PH}} \quad (2)$$

From Equation (2) the q''_{PC} for each section was estimated and the total heat is the summation of the heat per section. Nine (9) five inch section and one (1) two inch section were used for the calculations.

Since the thermal conductivity of the pyrotile varies with temperature, an attempt to compensate for the change in thermal conductivity of the pyrotile was included by varying the thermal conductivity in Equation (2) as a function of the average section temperature. Values used for the thermal conductivity of the tile as a function of temperature are shown in Figure D3.

Equation (1) is also used to estimate the temperature gradient from the hot side of the pyrotile to the inside diameter of the simulated element. The thermal conductivity of graphite as a function of temperature is shown in Figure D4. Solving Equation (2) for T_{ID} :

$$T_{ID} = \frac{q''_{ID} \ln \left(\frac{r_{PH}}{r_{PC}} \right) D_{ID}}{2 k(t)} + T_{PH} \quad (3)$$

The value of q''_{ID} for each section was estimated from q''_{PC} (Equation (2)):

$$q''_{ID} = q''_{PC} \frac{D_{PC}}{D_{ID}} \quad (4)$$

To estimate the surface temperature of the heater the radiation heat transfer relationship was used for infinite cylindrical bodies and solved for T_{HS} ,

$$q = \frac{A_{HS} (T_{HS}^4 - T_{ID}^4)}{\frac{1}{\epsilon_{HS}} + \frac{A_{HS}}{A_{ID}} \left(\frac{1}{\epsilon_{ID}} - 1 \right)}$$

or

$$T_{HS} = \left[\frac{q''_{HS} \frac{1}{\epsilon_{HS}} + \frac{D_{HS}}{D_{ID}} \left(\frac{1}{\epsilon_{ID}} - 1 \right)}{\sigma} + T_{ID}^4 \right]^{1/4} \quad (5)$$

where

$$q''_{HS} = q''_{ID} \frac{D_{ID}}{D_{HS}}$$

and ϵ_{HS} and ϵ_{ID} is the emissivity of the surfaces. Because of furnace and model size limitations, the maximum heater diameter allowed was 1.00 inch at the cold end; therefore, a current required to yield the heat flux requirements has to be estimated. This current will be the design current during the test. The heat required for an electrical resistance heater element is

$$Q = I^2 R = \frac{I^2 \rho(t) L 4}{\pi D_{HS}^2}$$

and

$$q''_{HS} = \frac{4 I^2 \rho(t)}{\pi^2 D_{HS}^3} \quad (6)$$

and solving for D_{HS} :

$$D_{HS} = \left[\frac{4 I^2 \rho(t)}{\pi^2 q''_{HS}} \right]^{1/3} \quad (7)$$

where

I = current in amperes

$\rho(t)$ = electrical resistivity as a function of temperature

From the above relationships the current for the heater based on the 1.00 inch diameter of the cold end can be estimated, and the required heater diameter as a function of axial heat flux can also be determined.

Using Equations (5) and (7), the required surface temperature of the heater can be calculated.

To estimate the centerline temperature of the heater it was assumed that the axial conduction is small compared to the radial conduction. In this case the conduction equation with heat generation is:

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) + \frac{q'''}{k} = 0 \quad (8)$$

Using the condition $\frac{dT}{dr} = 0$ at $r = 0$ and $T = T_{HS}$ at $r = r_{HS}$, Equation (8) has the following solution:

$$T - T_{HS} = \frac{q'''}{4k} (r_{HS}^2 - r^2) \quad (9)$$

at $r = 0$, $T = T_C$ and using Equation (9)

$$T_C - T_{HS} = \frac{q''' r_{HS}^2}{4k} \quad (10)$$

and the temperature distribution in dimensionless form is

$$\frac{T - T_{HS}}{T_C - T_{HS}} = \left(1 - \frac{r}{r_{HS}} \right)^2 \quad (11)$$

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Since in the heater design the temperature difference from T_{HS} to T_C is required, Equation (10) applies. Equation (10) in terms of current, $\rho(t)$, and radius becomes:

$$T_C - T_{HS} = \frac{I^2 \rho(t)}{4\pi^2 k r_{HS}^2} \quad (12)$$

The previous equations were used to estimate the heater designs. Typical designs using this formulation are drawings NT 701509 and NT 701516. Both stepped and continuous taper heaters have been manufactured.

The resistance of the heater is calculated, using the relationship

$$R_T = \sum \rho \frac{dx}{A(x)}$$

where dx is the incremental length of the heater and $A(x)$ is the relationship for the cross sectional area of the heater.

From this value of resistance and the calculated current the total power output of the final heater can be correlated with the original requirements of heat flow through the pyrotile.

MAJOR DESIGN CONSIDERATIONS

Design considerations which tended to confound the problem of predicting the operation of the tapered graphite heaters are discussed below.

The first problem to be considered is the electrical resistivity dependence of graphite as a function of temperature. Figure D5 indicates the scatter of data from different sources is quite large. The resistivity data used for the design of the heaters was obtained from tests conducted in the A-2 furnace. The resistivity was estimated from the relationship

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$$\rho(t) = [1.42 + .742 \times 10^{-4} T] 10^{-3} \Omega - \text{cm}$$

where T = absolute temperature in $^{\circ}\text{R}$. It was found that this value of resistivity was too high to obtain an acceptable correlation with test results. From full length heaters that were tested over the temperature range of interest, it was determined that an acceptable value is $0.9 \times 10^{-3} \Omega - \text{cm}$. This value was used to correlate the data from the HHT-7 Build 4 Test 1 run.

The second design problem was the uncertainty of the size of gap between the simulated element, filler strips and pyrotilite. During heating of the model the simulated core will tend to expand and depending on the efficiency of the lateral support system the bundling load could change enough to cause larger flow gaps in the core. If these gaps exist, the amount of power required to obtain the desired temperature distribution on the hot side of the pyrotilite could be increased due to additional heat absorption by the hydrogen flowing through the core. The mass flow rate through the core was approximated by assuming flow through parallel flat plates. Applying the equation of motion and simplifying assuming no pressure gradient in the "y" or "z" direction

$$0 = - \frac{1}{\rho} \frac{dP}{dx} + \frac{\mu}{\rho} \frac{d^2 u}{dy^2}$$

Solving for u the axial velocity,

$$u_X = - \frac{1}{2\mu} \frac{dP}{dx} y (h - y)$$

the mass flow rate is

$$\dot{m} = b \int_0^h \rho_m u_X dy \cong - \frac{\rho_m b}{12\mu} \frac{dP}{dx} h^3$$

where

b = width of passage

h = height of passage

It can be seen that the flow rate is directly proportional to h^3 . For values in the order of .001 to .003 inches the flow rate through the core is small compared to the total flow of the model. The amount of heat absorbed by the interstitial hydrogen flow was estimated on this basis.

The third design problem is predicting a representative thermal conductivity for the insulating tile. Rejected raw material was used to manufacture the configuration required for Build 4 Test 1 and the condition of some of the tile and the basal plane orientation was not known; however, when correlating the data of Build 4 Test 1 the variation due to this condition did not appear to have any adverse influence on the results.

All estimates of the model were based on the assumption that the radial heat conduction was much greater than the axial conduction. This appears to be an acceptable assumption except that at the hot end the actual temperature appears to be slightly lower than the estimated. In future heater designs, the heat flux at the hot end could be increased in order to compensate for the axial conduction loss, or the heater could be designed so that the drop of the temperature profile at the hot end would not affect the model profile.

HEATER TEST RESULTS

The heater design used for this test was NT 701509-102. The heater was operated in a stagnant helium atmosphere in the A-10 furnace with only the electrical conducting parts. A summary of the temperatures and power requirements are listed in Table D1.

The duration of the test was approximately 50 minutes during which several different power conditions were imposed on the heater. The results of the corrected recorded temperature versus axial station at different power levels are shown in Figure D6.

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Following the test a visual inspection of the heater element was made. The heater showed severe pitting along the heater surface but was not damaged otherwise. From the voltage drop and the current the average resistance of the heater was computed. Since the physical dimensions of the heater were known and using $R = \rho x/A$ the average resistivity was estimated as $0.9 \times 10^{-3} \Omega - \text{cm}$. This value was used in correlating the model temperatures.

MODEL TEST RESULTS

The heater used in the model test was NT 701509-101 which incorporates a gradual taper along its length instead of a stepped profile heater (NT 701509-102) used in the heater test. The resistance of the heater was found from the relationship

$$R_T = \frac{4\rho}{\pi} \int_0^x \frac{dx}{D^2(x)}$$

Using $\rho = \text{constant}$, the resistance was calculated at

$$R_T \cong 41.55 \times 10^{-3} \Omega$$

With this resistance value and the test power level of 130 KW, the predicted current is 1770 amperes and the voltage drop approximately 73.5 volts. The actual test results yielded a current of 1855 amperes at 70 volts. The error in the current estimation is approximately 4.8%. The actual average resistance of the heater calculated from the test data was $70V/1855A = 37.73 \times 10^{-3} \Omega$.

The resistance of the heater on a stepped section basis using a constant resistivity yields $38.6 \times 10^{-3} \Omega$, which is very close to the actual average resistance. Using this resistance value, the resistivity for this temperature range was calculated to be $0.9 \times 10^{-3} \Omega - \text{cm}$.

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Referring to Figure D2, the thermal design diameter of the hot side of the pyrotille was assumed to be an average of the innermost edge of the tile and a diameter described from a point where the adjacent tiles meet. These dimensions were scaled as 3.132 inches and 3.25 inches, respectively. From Equation (2) the value of $\ln r_{PC}/r_{PH} = .093$, which yielded

$$q''_{PC} = \frac{\Delta T k(t)}{7034.8176} \text{ BTU/sec-in}^2$$

Using the above relationship, the total heat requirement was calculated at 103 KW. However, from the test results, the actual power measured was in the order of 130 KW. In order to correlate the data within a reasonable accuracy the value of the hot side pyrotille diameter was adjusted to an effective diameter of 3.25 inches to compensate for the thermal expansion of the core diameter during the actual test operation. This new diameter corresponds to the diameter of the hot side pyrotille at a point radially outward from where the adjacent tiles meet. The new effective diameter reduced the value of $\ln r_{PC}/r_{PH}$ from .093 to .075. Re-estimating the total heat requirement using this new value for the $\ln r_{PC}/r_{PH}$ yields a total heat requirement of 128.5 KW which is very close to the 130 KW measured during the test. Figure D7 shows the effect of varying pyrotille hot side radius as a function of total power required.

Since the temperature profile was close to the expected shape, the heat flux per section of the heater was extrapolated so the total heat output would yield 130 KW.

The pyrotille hot side temperature is equal to the cold side plus the temperature drop. The actual cold side pyrotille temperature is not known but from the tests, reflector material temperatures were measured and plotted in Figure D8 along with the estimated and actual pyrotille hot side profile.

The pyrotille hot side temperature towards the exhaust end of the core is lower than expected. This temperature difference was attributed to the axial conduction into the large electrodes and support parts at the hot end of the model.

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Comparing Figure D1 with Figure D8 the original cold pyrotille temperature profile is lower than the test model profile. The distribution in Figure D1 was based on 0.035 lbm/sec of hydrogen and 103 KW to be absorbed; in Figure D8 there was .025 lbm/sec of hydrogen plus approximately 0.0044 lbm/sec of helium and 130 KW of power. As expected the cold side distribution was not a straight line as assumed but was logarithmic.

SAMPLE CALCULATIONS

Sample calculations between axial stations 40 and 45 will be shown in order to indicate the method of calculation. The temperature distributions in Figure D8 for T_{PH} and T_{gas} will be utilized for the hot side pyro and cold side pyrotille temperatures. The assumption that the cold side pyrotille temperature is the same as the gas temperature will not be in great error since the heat transfer coefficients in this area are quite large. Using Equation (2)

$$q''_{PC} = \frac{(T_{PH} - T_{PC}) 2 k(t)}{D_{PC} \ln \frac{D_{PC}}{D_{PH}}}$$

where

$$T_{PH} = 4650^{\circ}R \text{ (Figure D8)}$$

$$T_{PC} = 1750^{\circ}R \text{ (Figure D8)}$$

$$k(t) = .47 \text{ BTU/hr-}^{\circ}F\text{-ft (Figure D3)}$$

$$D_{PC} = 3.502 \text{ in.}$$

$$D_{PH} = 3.25 \text{ in.}$$

$$q''_{PC} = \frac{(4650 - 1750) (2) (.47)}{(3.502) \ln \frac{3.502}{3.25} (12) (3600)}$$

$$q''_{PC} = .2402 \text{ BTU/sec-in}^2$$

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Next estimate the heat flux at the inside diameter of the simulated element.

$$q''_{ID} = q''_{PC} \frac{D_{PC}}{D_{ID}} = \frac{(.2402)(3.502)}{(1.375)} = 6.11 \text{ BTU/sec-in}^2$$

Using Equation (3), estimate the temperature at the inside diameter of the simulated element.

$$T_{ID} = \frac{q''_{ID} \ln \frac{D_{PH}}{D_{ID}} D_{ID}}{2 k(t)} + T_{PH}$$

where

$$T_{PH} = 4650^{\circ}\text{R} \text{ (Figure D8)}$$

$$D_{ID} = 1.375 \text{ in.}$$

$$D_{PH} = 3.25 \text{ in.}$$

$$q''_{ID} = 0.611 \text{ BTU/sec-in}^2$$

$$k(t) = 30 \text{ BTU/hr-}^{\circ}\text{F-ft (Figure D4)}$$

$$T_{ID} = \frac{(.611) \ln \frac{3.25}{1.375} (1.375) (3600) (12)}{2(30)} + 4650$$

$$T_{ID} = 520.2 + 4650 \cong 5170^{\circ}\text{R}$$

To find the diameter of the heater, the heat flux is required according to Equation (7) but in order to find the heat flux the diameter is required. In Equation (5) the diameter is also required for heat flux consideration and also to yield the correct radiation shape factor.

Therefore, an iteration process between Equations (5) and (7) will be used since another unknown which is a function of temperature, the electrical resistivity, has to be considered.

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From Equations (5) and (7) and assuming $D_{HS} \cong 0.727$ inches and

$$q''_{HS} = q_{ID} \frac{D_{ID}}{D_{HS}} = \frac{(0.611)(1.375)}{(0.727)} = 1.55 \text{ BTU/sec-in}^2$$

$$D_{HS} = \left[\frac{4(1.77)^2 \times 10^6 (0.9) \times 10^{-3} \times 3.412}{\pi^2 (1.155)(2.54)} \right]^{1/3}$$

$D_{HS} = 0.716$ inches; the error is 1.53% and closer approximations can be made if required.

Where $I = 1770$ amperes
 $\rho(t) = 0.9 \times 10^{-3} \Omega\text{-cm}$

When the $\rho(t)$ is not assumed constant, the T_{HS} must be estimated and the $\rho(t)$ corrected.

$$D_{HS \text{ average}} = \frac{.727 + .716}{2} = .721 \text{ inches}$$

$$T_{HS} = \left\{ \frac{1.155 \left[\frac{1}{.77} + \frac{.721}{1.375} \left(\frac{1}{.77} - 1 \right) \right] (3600)(144)}{.1714} + 5170^4 \right\}^{1/4}$$

$$T_{HS} \cong 5910^\circ\text{R}$$

where $\epsilon_{HS} = .77$
 $\epsilon_{ID} = .77$
 $T_{ID} = 5170^\circ\text{R}$
 $\sigma = 0.1714 \text{ BTU/hr-}^\circ\text{R-ft}^2$

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If the $\rho(t)$ value was not estimated correctly, a new $\rho(t)$ would be assumed and the D_{HS} and T_{HS} could be re-estimated until the dependency of the unknowns balance. A typical heater diameter versus axial station plot is shown in Figure D9 for a heater with a total power output of 103 KW.

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Table D1
HHT-7 Heater Test Results

Test Number	E	IMV.	T ₁ ' °F	T ₁ °R	T ₂ ' °F	T ₂ °R	T ₃ ' °F	T ₃ °R	T ₄ ' °F	T ₄ °R	PKW.
1	40	3	2300	2960	2200	2880	2660	3400	2600	3330	42.0
2	40	3	2370	3060	2320	3000	2740	3490	2600	3330	42.0
3	52	4	2660	3400	2510	3220	3150	4030	2900	3700	72.8
4	--	-	2790	3580	3710	3480	3160	4040	3060	3910	----
5	61	4.6	2880	3680	2870	3670	3600	4640	3410	4380	98.1
6	62	4.7	2880	3680	2880	3680	3760	4870	3410	4380	101.98
7	71	5.2	3040	3880	3040	3880	3940	5130	3770	4900	129.2
8	72	5.3	2540	3260	2800	3580	4120	5400	3900	5070	133.56
9	82	5.9	----	----	----	----	3840	5000	4200	5500	169.32
10	82	5.9	----	----	----	----	4000	4200	4000	5200	169.32
11	82	5.9	3440	4420	----	----	4343	5880	4280	5740	169.32

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Build 4 Test 1 Axial Temperature Profile

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Figure D-2

Build 4 Test 1 Core Cross Section

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Figure D-3

Thermal Conductivity of Pyrographite
Perpendicular to Basal Planes, "C" Direction

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Figure D-4

Thermal Conductivity Versus Temperature for Non-Fueled Elements

(WC-WHO 6-01) ALIADISER

Figure D-5

Electrical Resistivity of Graphite (With Grain)

Figure D-6
Temperature Versus Axial Station at
Various Power Inputs and Flow Requirements

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Figure D-7

Hot Pyrotile Radius Versus Total Power Input of Heater

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Figure D-8

Heater Diameter Versus Axial Station for NT 701516

Figure D-9
Temperature Versus Axial Station

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